

FINAL REPORT

for

REVIBRATION OF CONCRETE FOR BRIDGE DECKS

PROJECT NO. 70-02-2, AGREEMENT NO. 12

Submitted to

OKLAHOMA STATE HIGHWAY DEPARTMENT
Oklahoma City, Oklahoma

By

DR. H. ALDRIDGE GILLESPIE

From

OFFICE OF RESEARCH ADMINISTRATION
UNIVERSITY OF OKLAHOMA
1000 Asp Avenue, Room 314
Norman, Oklahoma 73069

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CHAPTER 1

INTRODUCTION

1.1 General

Increased concern over high maintenance costs has led to several studies on the deterioration of the reinforced concrete bridge decks in various parts of the United States during recent years. These studies have mainly concentrated on obtaining information concerning:

1. The types and extent of deck deterioration
2. Causes of the various types of deterioration
3. Methods for retarding and/or eliminating deterioration of existing bridges now showing deterioration.
4. Changes in construction techniques to reduce deterioration of bridges in the future.

Of the different sophisticated construction techniques being considered to improve the quality and performance of a bridge deck during its life time, surface revibration of the concrete deck during placement appears to be a promising and practical construction procedure.

This Final Report contains the results of a study of the potential benefits of surface revibration on bridge deck concrete subjected to a wide variety of crack inducing conditions, among which are the effects of weather (temperature, wind, and humidity variations), mix variations (causing all kinds of shrinkage conditions), placement and finishing techniques, surface curing differences, together with a wide variety of revibration conditions and applications.

Successful closure of environmentally and physically induced cracking has been achieved as well as improvement in the surface and physical properties of concretes otherwise considered too poor for bridges. Control slabs have demonstrated essentially every kind of cracking , including longitudinal, transverse, pattern,

crazing, scaling, spalling, and that most difficult to produce experimentally, horizontal weakness plane and cracking at the top steel level.

1.2 Effect of Consolidation of Fresh Concrete on the Properties of Concrete

Vibration of concrete has been universally accepted as a practical means of handling stiff, low water-cement ratio concrete. Effective compaction improves many concrete properties such as compressive and flexural strengths, bond between concrete and reinforcement, density, homogeneity, bond between successive layers of concrete, water tightness and resistance to weathering. Because a concrete mass dries and shrinks progressively from its exposed surfaces, the contracting surfaces tend to become structurally separated from the more plastic core. If the shrinkage differential is great due to rapid surface set and/or excessive moisture content, (which can be brought about in the upper zone of a slab due to bleed water) loss of strength can be severe. The resulting concrete becomes a type of 3-dimensional jigsaw puzzle.

Compaction of concrete has a decisive influence on the quality and appearance of the finished product. The strength and other properties of concrete are highly dependent on the water-cement ratio. This is so, however, only if the concrete when placed is compacted to a dense, homogeneous mass containing only a small percentage of entrapped air voids. If insufficiently compacted, the concrete will contain voids and overtly stressed intersurfaces to a greater or lesser extent. The greater the percentage of voids, the lower will be the strength of the cured concrete, and the greater will be its susceptibility to effects of weather.

1.3 Revibration and Its Effects

Structural properties of most concrete can be improved by surface revibration; in disturbing the hardening process of the concrete by revibration, it is principally the mortar that is affected. Several conditions are affected by surface revibration which contribute to the likelihood of better structural properties:

1. The mortar and concrete become more densely consolidated, thereby permitting more advantageous deployment of the hydration products;
2. The water-cement ratio of the paste in general is improved by the extent of evaporation, absorption and bleeding having taken place to a greater or lesser extent before revibration;
3. Internal stress patterns caused by early shrinkage and gel growth are relieved by the reliquification of the mass;
4. The vibratory disturbances alter growth and formation of hydration products, apparently enhancing the formation of those hydrates which contribute to improved strength.

In considering the effects of revibration, one might picture the structure of the cement paste during the setting process: soon after the mixing water begins to associate with material at the surface of the cement grains, a colloidal gel is formed, gradually increasing in volume and consistency as further solution, hydrolysis and hydration take place. It is possible that initial set corresponds to the time when tentacle-like streamers of gel, growing from the individual grains of cement, meet and cause a rather rapid stiffening of the paste. It is possible, also, that there may be formed within the paste structure some crystalline products which aid in stiffening the partially set mass. During the setting process, there occurs a characteristic contraction or settlement of the mass. Owing to friction between, and wedging of the aggregate particles in concrete, this tendency to contract is probably not fully satisfied, hence the application of external pressure likely will cause further consolidation.

Until the gel has attained considerable strength and rigidity, the concrete mass, when revibrated, can again be made to act as a fluid, although after several hours have elapsed from the time of mixing, considerable effort may be required. From observations on concretes revibrated after lapse of various intervals from the time of mixing, there appear to be three general stages as regards response to revibration.

In the first stage, while the mass slowly stiffens with time, the concrete is essentially plastic and is readily "fluidified" by vibration, although the time required to do this may be two or three times that required to consolidate the mass initially. In this stage, also, as the concrete is brought to the effectively fluid condition, a noticeable amount of air may be expelled from the mass.

In the second stage, which perhaps begins at a time prior to, but nearing, initial set, the effect of revibration appears at first to cause a slight disruption of the mass. Continuation of the vibration, however, causes the mass slowly to "melt" together again, generally with the expulsion of quantities of free water and air. In relation to the setting process, it is possible that this behavior would indicate first a rupture of the filaments of gel which have begun to give definite structure to the stiff mass, and then a reduction of the gel to a viscous condition together with a further consolidation of the partially settled mass of particles. In this stage considerably more time and effort are required to reconsolidate the mass than required initially to compact the fresh concrete.

In the third stage the concrete is either so stiff that if disrupted it is impossible to reconsolidate it effectively with ordinary vibratory equipment, or it is too stiff to be visibly affected.

1.4 Surface Application of Vibration

Vibratory screeds have been widely used in the placement and finishing of slabs and pavements. In the case of pavements, both internal and surface vibration are typically used in the laydown process. However, after this initial placement, it is not practical to obtain the benefits of revibration by use of spud or tube style internal vibrators.

Surface vibration alone, without internal, has had limited use in the placement of pavements. The feasibility of construction and reduction of several of the variables associated with surface vibration was comprehensively studied at the Road Research

Laboratory in England ("The Compaction of Concrete By Surface Vibration," R.H.H. Kirkham, Budapest Conference, 1963). The potential benefits of pre-initial set deflection crack closure by surface revibration has also been reported ("Revibration of Retarded Concrete for Continuous Bridge Decks," Report 106 NCHRP, H.R. Hilsdorf, 1969). Other reports, of course, contain further data but the foregoing are particularly of value in consideration of the present study. It was shown therein that the use of surface vibration does in fact produce those same benefits as interior vibrations and that surface revibration has additional benefits which pertain to solution of bridge deck concrete problems. Specifically, the Hilsdorf report shows that revibration can effectively close deflection induced cracking when performed prior to attainment of 60 psi penetration resistance, that the resulting surface is comparable to the control surfaces, and that other physical properties are insignificantly altered. Hilsdorf's study was restricted to a single vibrator at two different ranges of centrifugal force: 180 lbs. and 720 lbs.

A floating type steel pan with mounted vibrators was used in the present study. Frequency and amplitude were varied through the use of several vibrators as well as through voltage variation and eccentric movement on several of the vibrators. To obtain an optimal frequency and nominal amplitude suitable for use with revibration, different vibrators with a frequency range of 2,000 to 10,800 cpm and nominal amplitudes varying from 0.006 to 0.036 inches were used.

An electrically powered vibrator was mounted on a pan 3'11" by 8" by 1/8". The vibrating pan was mounted on a carriage supporting system which permitted it to roll along the sides of the formwork. The use of rubber cushions minimized the transmission of vibrations from the pan directly into the formwork. The arrangement is shown in Figure 1.

1.5 Cracking in Concrete

Cracking of concrete is a source for continued and accelerated deterioration of the concrete. While the penetration of water and moisture or deicing salts corrode the

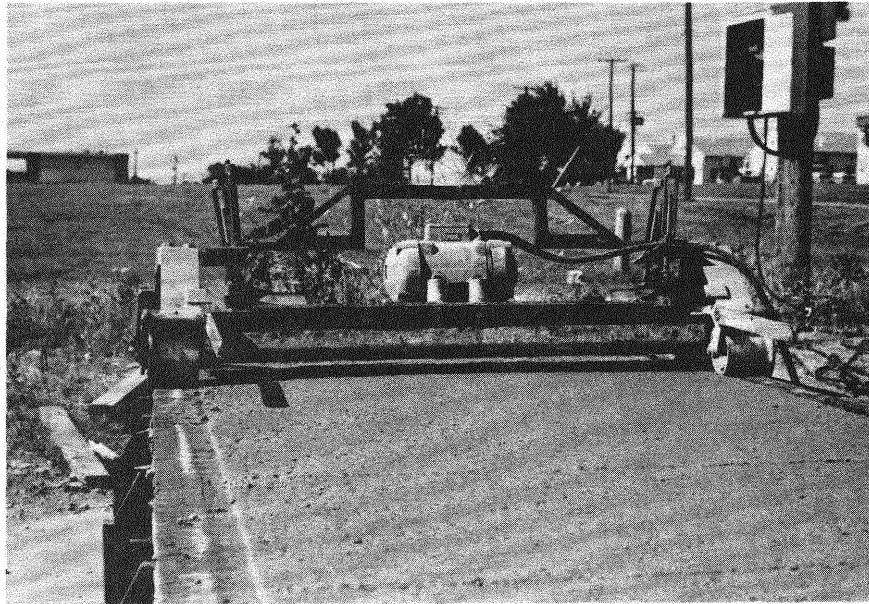


Figure 1 a. Pan and Carriage Type Vibrating Mechanism.

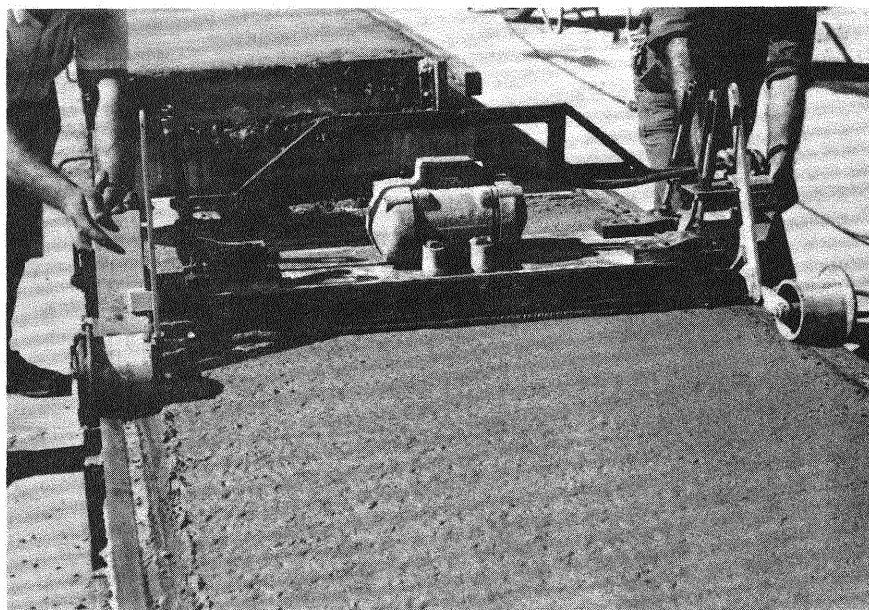


Figure 1 b. Vibrating Mechanism in Operation.

reinforcement, collection of water in the crevices and saturation of the concrete below the deck surface accentuates the deterioration caused by freezing and thawing of the concrete. The expansive nature of the corrosion products of the reinforcement cause high stresses in the concrete cover which results in weakened planes near the surface. These planes of weakness are either vertical or horizontal in position. Where the stress intensity exceeds the tensile strength of the concrete, cracks open up.

Resistance to subsidence of the concrete during the bleeding period and early drying shrinkage appear to be the main causes for the formation of the longitudinal and some transverse cracks. Negative moment, of course, adds to both kinds of cracking. In addition, inadequate cover over the rebars contributes to the growth of the cracks.

Of the different types of deterioration that develop in the concrete bridge decks, the formation of cracks while the concrete still is in a plastic state seems to be of greatest importance. In fresh concrete, shrinkage of the cement paste is restrained either by aggregates or steel reinforcement which results in tensile stresses and subsequent cracking of the fresh concrete. Deformation of the formwork or the supporting structure of the bridge deck due to the weight of the concrete causes severe stresses in the fresh concrete. Tensile stresses develop in the fresh concrete in the area of the negative bending moment region which lead to transverse cracks. Furthermore, in deeper slabs top steel offers resistance to the fresh concrete during the process of settlement. The concrete below the reinforcement gradually settles down leaving a gap under the reinforcement. The bleeding water collects under the rebars. This enhances the possibility for the formation of the horizontal plane of weakness, and in some instances, resistance to subsidence causes the opening of the vertical cracks extending from the top reinforcement to the surface of the concrete bridge decks. High temperature and wind velocities during casting are favorable conditions for crusting which again causes the formation of planes of weakness.

The production of control specimens included those that had insofar as possible all types of common cracking as well as completely satisfactory concretes.

With the intention of producing defective (cracked) specimens (slabs) as well as good and sound specimens, the following variables were used as the DS series:

1. Top reinforcement cover, 1/2" to 2" .
2. Water-cement ratio, 0.8 to 0.39.
3. Insufficient consolidation of low slump concretes 0" to 2" slumps.
4. Overworked high paste-aggregate ratio concretes, 0.4 to 0.6.
5. High wind and temperatures at cast time (20 mph+ , 90°F+).
6. Curing compound (linseed oil emulsion) omitted.
7. Dispersed spacing of reinforcement, lateral and longitudinal (up to 12").

Each kind of cracking has been reproduced in the control slabs of this project, and the effects of surface revibration at the several stages of stiffening of the concrete (measured by the penetration resistance) have been studied. In general, it can be stated that revibration has been beneficial in eliminating or reducing all kinds of cracking.

CHAPTER 2

EXPERIMENTAL SETUP AND PROCEDURE

2.1 General

The relative merits of surface revibration can be ascertained only if it can be shown that a significant difference existed when compared to concrete slabs constructed using modern concrete designs, placement and finishing techniques. Control slabs were, therefore, required which would demonstrate the several kinds of cracking as well as slabs that were perfectly sound and acceptable, the latter being required to show any negative influence produced by revibration.

The production of control slabs, defective series (DS) was the first item of experimentation. In addition to the initial series of control slabs, 55 total, further companion control slabs were cast along with those being revibrated. A total of 81 control specimens were cast and an additional 16 with retarder in the concrete, for a total of 97 slabs (94 were eventually used as control specimens). Surface revibration was performed on a total of 118 slabs, of which 36 contained retarder.

All slabs were cast in an out-of-doors area subject to all weather conditions normal to Oklahoma. Ready mix concrete was procured from a single plant with 10 min. transit time to the casting site. The material source remained constant during the 2 years of casting. All materials met Oklahoma Highway Department (OHD) specifications.

2.2 Concrete

Concrete mixes were designed using OHD No. 57 coarse aggregate (1" to 1 1/2" MSA) and OHD sand (Newcastle), the sand comprising about 42% of the total aggregate. Type I cement was used throughout, as well as a common OHD approved air entraining admixture. As the concrete arrived on the casting site, a slump test

was taken, unit weight determined, mortar sieved (No. 4 minus) for penetration tests as well as 3/8 inch minus for an alternate penetration test, 12 @ 6 x 12 inch cylinders cast for strength tests, and an air content measurement performed.

The properties of concrete associated with each slab are tabulated in Table 1, Properties of Field Concrete, and the general set-up for performing the several ASTM tests is shown in Figure 2.

Variations in water-cement ratios were part of the program, and in most cases 2 to 5 inch slump concrete with 5% air was specified and in some cases where eight (8) slabs were cast from one batch, water was added at the job site after sufficient concrete was removed from the mixer for casting for the first four (4) slabs. The addition of retarder into the mixer for the DSR and RVSR series was also performed at the job site.

The overall mean slump was 6.35 inches with values ranging from 11.5 inches to 1.5 inches. Mean of the air content was 4.58% with a range from 0.5% to 9.5%.

An emulsified linseed oil curing compound was applied to the surface of some slabs. However, so effective was the compound in reducing shrinkage cracking that it was not extensively used in the revibrated series since it did not permit a good evaluation of the effectiveness of revibration in eliminating cracking.

2.3 Formwork

Close duplication of field conditions was deemed necessary, and the formwork was constructed accordingly. All forms were 4 ft. x 8 ft. x 8 in. built with wood and treated between each use with form oil. Interior supports under the plywood bottom were set at 2 ft. - 8 in. intervals thereby producing a continuous slab effect over 2 interior supports. The thickness of the plywood bottom of the form was so designed to permit about $6 \times 10^{-4} \text{ inch}^{-1}$ curvature, i.e., a center-span deflection of about 0.24 inches. (See Figure 2.)

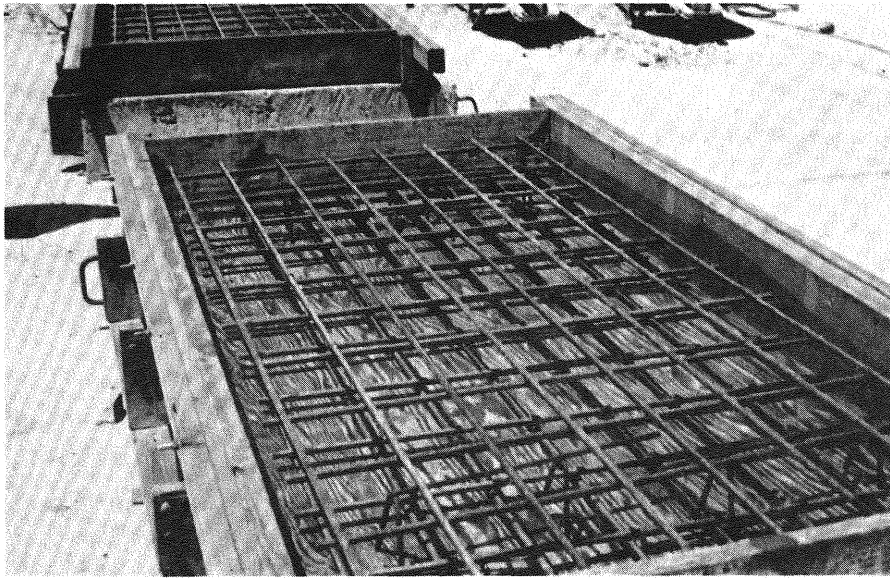
Table 1
Properties of Field Concrete

Slab Type and Number	Water/Cement Ratio	Slump in.	Air Content %	Unit Weight pcf	Compressive Strength psi		Retarder		Curing Agent
					7 days	28 days	Type	Amount oz./bag	
DS - 1	0.6	8	1.5	150		1937			
DS - 2 to 5	0.6	6.5	4	150	1982*	1995*			
DS - 6 to 7	0.68	7.5	4.5	150	1320	1570			
DS - 8	0.68	7	4.5	150	1497	1570			
DS - 9 to 11	0.68	8	5.0	154	1532	1183			
DS - 12 to 14	0.45	2.5	5.0	145	2770	2483			
DS - 15 to 17	0.68	8	6.0	141	1281	1145			
DS - 18 to 19	0.39	2	4.0	146	set too rapidly, not usable				
DS - 20 to 21	0.48	9.5	.5	144	3910	4050			Yes
DS - 22 to 23	0.48	5.5	.5	144	3910	4050			Yes
DS - 24 to 27	0.84	9.25	-	144	1616	1677			Yes
DS - 28 to 29	0.42	2.5	4.5	149	5473	5830			Yes
DS - 30 to 31	0.42	6.5	4.5	149	5473	5830			Yes
DS - 32	0.62	1.75	4.25	148	2673	3108			Yes
DS - 33	0.73	6.75	4.25	148	2673	3108			
DS - 34	0.73	6.75	4.25	148	2673	3108			Yes
DS - 35	0.73	6.75	4.25	148	2673	3108			
DS - 36 to 37	0.59	8	4.2	144	2733	3405			Yes
DS - 38 to 39	0.59	8	4.2	144	2733	3405			
DS - 40 to 41	0.4	4.5	4.8	144	2723	3603			Yes
DS - 42 to 43	0.4	4.5	4.8	144	2723	3603			
DS - 44, 46	0.61	8	3.5	148	3763	3731			Yes
DS - 45, 47	0.61	8	3.5	148	3763	3731			
DS - 48 to 49	0.47	3.75	4.6	146	2967	3436			Yes
DS - 50 to 51	0.47	3.75	4.6	146	2967	3436			
DS - 52	0.77	4.25	5.4	144	2171	3068			Yes
DS - 53 to 55	0.77	4.25	5.4	144	2171	3068			
DS - 56 to 58	0.61	1.25	5	148	4130	4448			
DS - 59 to 62	0.59	3.75	5	148	1906	4278			
DS - 64	0.55	6	5.9	143	1718	3450			
DS - 65, 66	0.49	5	9.5	138	2530	2276			
DS - 67	0.41	5	4.5	147					
DS - 68	0.41	5	4.5	147					Yes
DS - 69, 70	0.43	6	4	145	3767	5423			
DS - 71	0.43	4.75	4.25	145	4515	5576			
DS - 72 to 75	0.55	4.5	4.5	145	3030	3322			
DS - 76	0.54	3.5	4	146	3878	4910			Yes
DS - 77 to 79	0.54	3.5	4	146	3878	4910			
DS - 80	0.7	5	4.5	138	2323	2510			
DS - 81	0.6	6	-	-					
RVS - 1, 2	0.77	5.5	4.5	144	2044	2460			Yes
RVS - 3, 4	0.77	5.5	4.5	144	2066	2460			
RVS - 5, 7	0.67	9	4.7	146	2795	2687			Yes
RVS - 6, 8	0.67	9	4.7	146	2795	2687			
RVS - 9, 11	0.66	5	3.8	140	2854	3678			Yes
RVS - 10, 12	0.66	5	3.8	140	2854	3678			
RVS - 13 to 16	0.55	3	3	149	4112	4726			
RVS - 17 to 20	0.39	4	3	149	3662	3936			

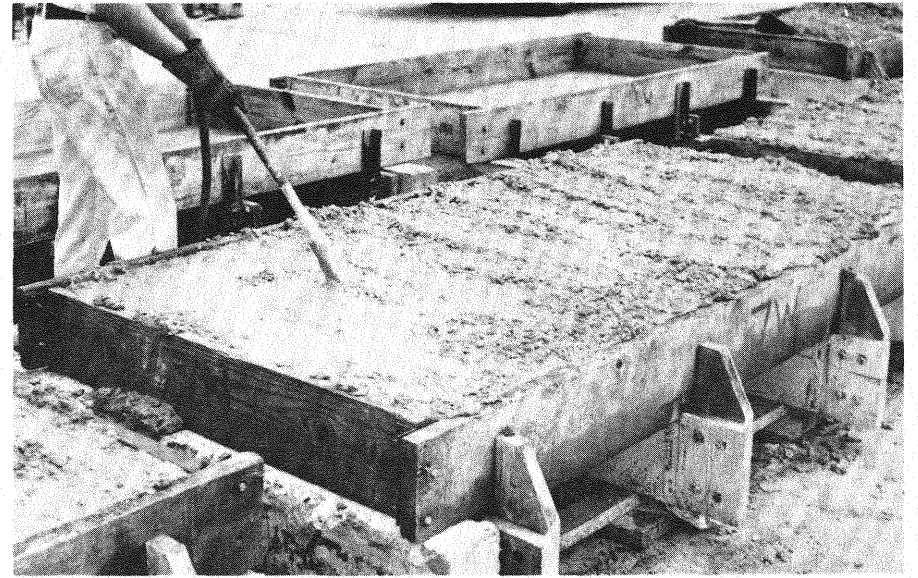
Table 1 (Continued)

Slab Type and Number	Water/Cement Ratio	Slump in.	Air Content %	Unit Weight pcf	Compressive Strength psi		Retarder		Curing Agent
					7 days	28 days	Type	Amount oz./bag	
RVS - 21, 22, 25 to 27	0.61	1.5	5	148	4130	4448			
RVS - 29, 30, 33, 34	0.59	3.75	5	148	1906	4278			
RVS - 37 to 39, 41 to 44	0.70	1.5	6	144	4166*	4452*			
RVS - 45 to 52	0.41	3.5	6.6	143	4470	5030			
RVS - 53 to 59	0.55	6	5.9	143	1718	3450			
RVS - 61 to 64, 67, 68	0.49	5	9.5	138	2530	2276			
RVS - 69 to 72	0.55	4	5	145	2953				
RVS - 75, 76	0.41	5	4.5	147					Yes
RVS - 77, 80	0.43	6	4	145	3767	5423			
RVS - 81 to 84	0.56	7	4	-	3448	4262			
RVS - 85 to 87	0.43	4.75	4.25	145	4515	5576			
RVS - 89 to 92	0.7	7	5.25	139	1751	2169			
RVS - 93	0.8	8	4	141	1467	2198			Yes
RVS - 94 to 96	0.8	8	4	141	1467	2198			
RVS - 97 to 99	0.7	5	4.5	138	4323				
RVS - 100 to 102	0.6	6	5.5	-					
DSR - 1	0.43	3.5	6	139	3855	4757	PDA-R25	4	
DSR - 2, 3	0.41	4.5	5.5	145	4279	5570	PDA-R25	4	
DSR - 4	0.43	5.5	8.5	139	4363	5211	PDA-R25	6	
DSR - 5	0.48	5.5	8.5	139	3272	4510	PDA-R25	4	
DSR - 6	0.65	6	7.0	137	3324	4609	PDA-R25	4	
DSR - 7	0.7	5.75	7.25	138	2069	3360	PDA-R25	6	
DSR - 8	0.65	5	6.25	138	3051	4580	PDA-R25	4	
DSR - 9 to 12	0.7	5	3	138	3324	4210	PDA-R25	4	
DSR - 13	0.75	11.5	5	136	2563	3550	PDA-R25	3	
DSR - 14	0.66	8	7	141		6020*	PDA-R25	6	
DSR - 15	0.47	7	6.5	140		5220*	PDA-R25	6	
DSR - 16	0.6	7.75	-	-			PDA-R25	2.4	
RVSR - 1 to 3	0.43	3.5	6	139	3855	4757	PDA-R25	4	
RVSR - 4, 5	0.41	4.5	5.5	145	4279	5570	PDA-R25	4	
RVSR - 6	0.43	5.5	8.5	139	4363	5211	PDA-R25	6	Yes
RVSR - 7, 8	0.43	5.5	8.5	139	4363	5211	PDA-R25	6	
RVSR - 9	0.48	5.5	8.5	139	3272	4510	PDA-R25	4	Yes
RVSR - 10, 11	0.48	5.5	8.5	139	3272	4510	PDA-R25	4	
RVSR - 12 to 15	0.53	5	3	139	5452	6366	PDA-R25	6	
RVSR - 16 to 18	0.65	6	6.5	137	3324	4609	PDA-R25	4	
RVSR - 19 to 21	0.7	5.75	7.25	138	2069	3360	PDA-R25	6	
RVSR - 22 to 24	0.65	5	6.25	138	2410	4580	PDA-R25	4	
RVSR - 25 to 27	0.75	11.5	5	136			PDA-R25	3	
RVSR - 28 to 30	0.66	8	7	141		6020*	PDA-R25	6	
RVSR - 31 to 33	0.47	7	6.5	140		5220*	PDA-R25	6	
RVSR - 34 to 36	0.6	7.75	-	-			PDA-R25	2.4	

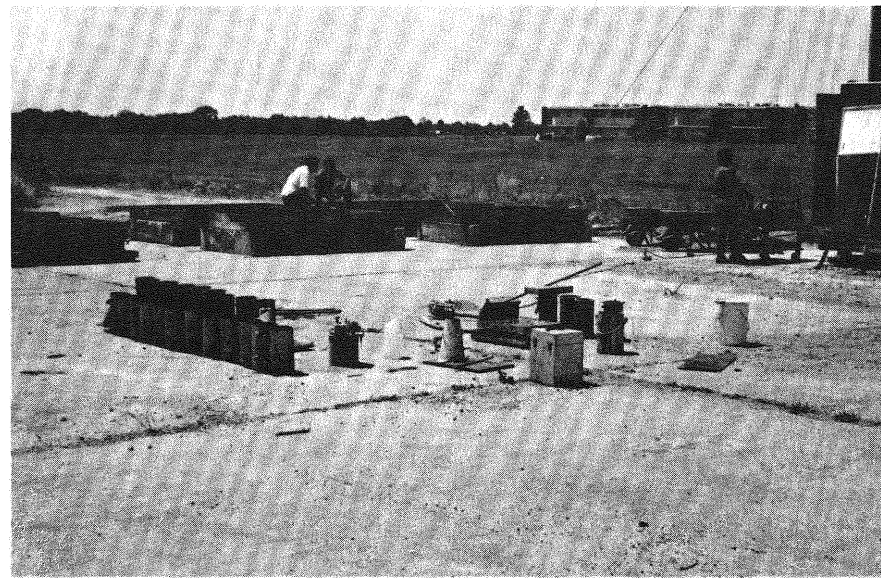
*Compressive Strength Values Beyond 7/28 Days.



(a)



(b)



(c)

Figure 2. Experimental Set-up for Casting Concrete Slabs.

A total of 8 slab forms were constructed and typically 4 were used for any one batch of concrete although on some occasions a double batch was ordered and all 8 were filled. Each slab had different variables represented in the reinforcement, cover, penetration resistance at time of revibration, or cure, etc., as outlined in the following.

A single series of 8 slabs was jacked up in the middle span producing very obvious deflection cracking. Figure 3 shows the setup and pre-revibration results of this formwork manipulation.

2.4 Slab Reinforcement

With but few exceptions, top and bottom steel mats were used in the slabs made of No. 4 reinforcing on 6 inch centers, wire tied at all joints.

During the early stages of the project several slabs (22 total) were cast to determine if a change in top bar spacing would significantly alter the cracking pattern. Also, larger reinforcing bars (No. 5 and No. 6) were used for the same purpose. Although a distinct reinforcing bar associated cracking can be seen with the 12 inch top bar spacing, there was neither more nor less cracking than with the No. 4 at 6 inches, and so the latter was used for all other slabs.

Standard steel rebar chairs were used for both top and bottom mats. The bottom steel was set consistently at 2 inches from the lower surface, while the top steel was positioned to vary the cover from 1/2 inch to 2 inches. The surface revibration process often left an effective final cover as much as 1/4 inch less than had been initially planned, due to additional consolidation during revibration.

2.5 Vibrators and Vibrating Pan

Internal vibration was given the fresh concrete during placement with a 2 inch square spud type vibrator (see Figure 2b).

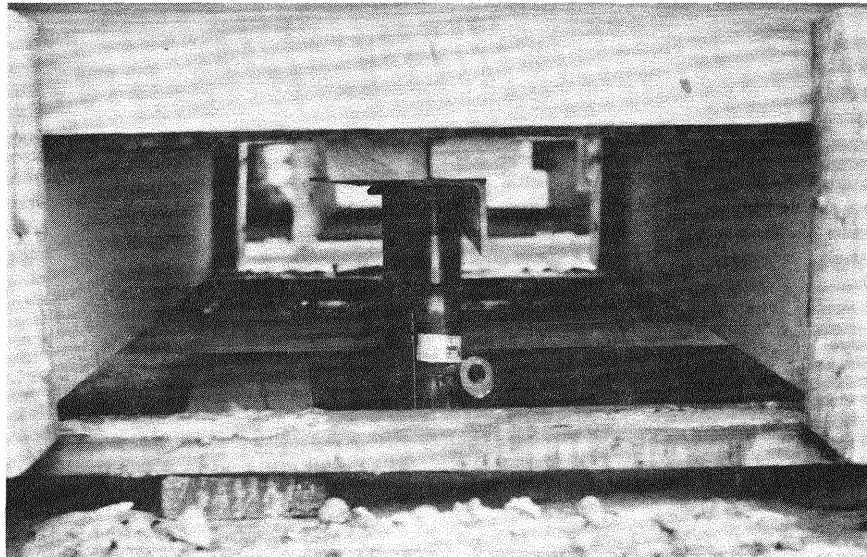


Figure 3 a. Jacking Device Under Mid-span of Slab.

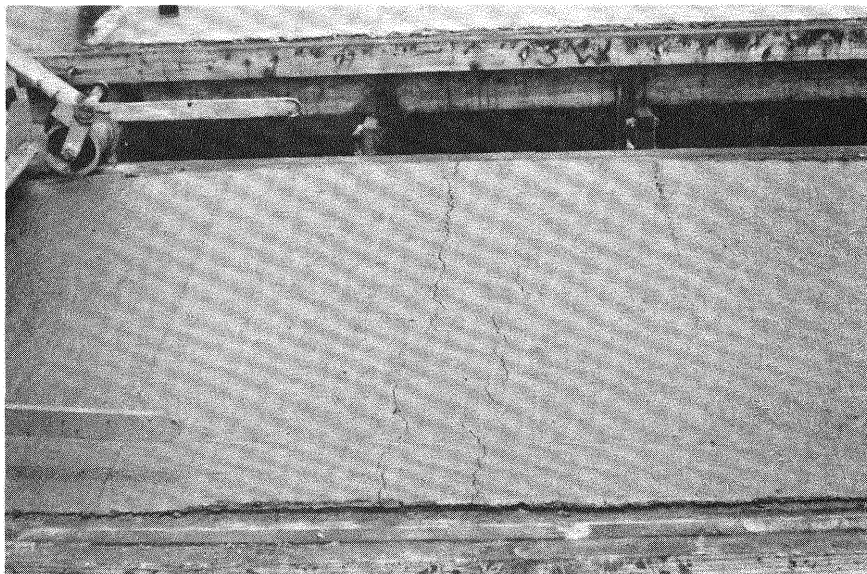


Figure 3 b. Cracking Induced by Jacking of Forms.

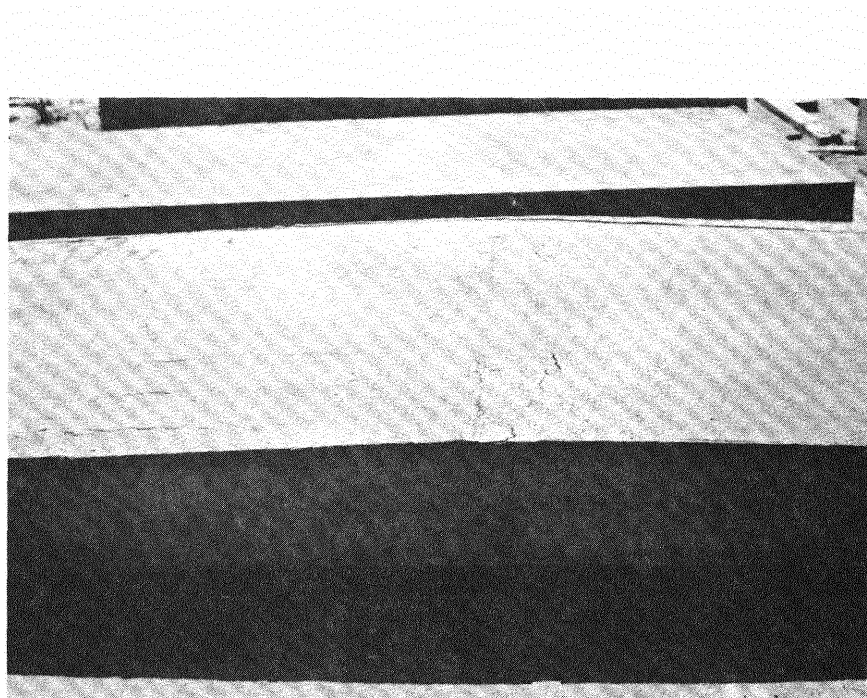
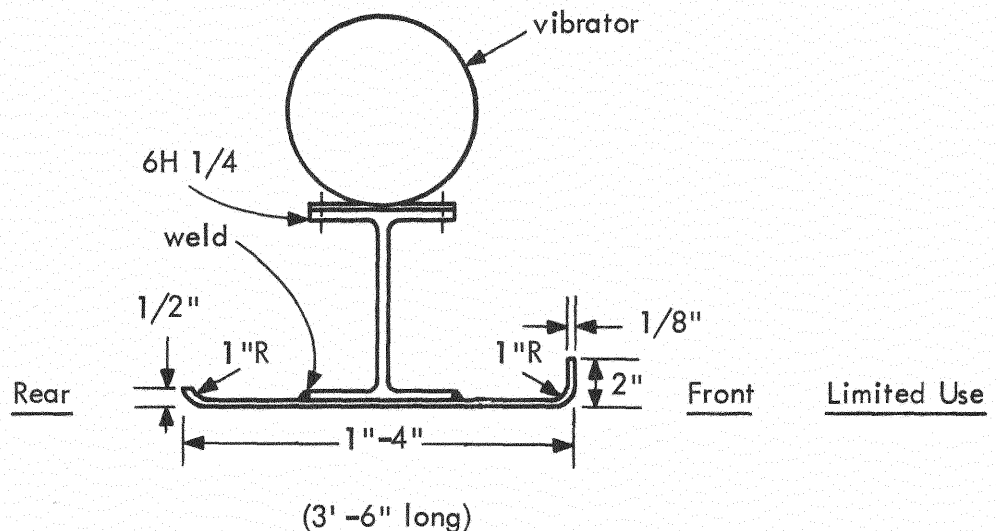


Figure 3 c. Transverse and Longitudinal Cracking Control Slab DS-49 as a Result of an Induced 2-inch Deflection in the Center of the Span.

Five separate vibrators were used in conjunction with the quasi-floating pan for revibrating the surfaces of the RVS and RVSR series of slabs. Details of each vibrator and its output when attached to the pan are given in Table 2. It must be noted that the calculated acceleration, g , is at the rated frequency which, in some cases, varied (decreased) when the pan was in contact with the fresh concrete and, therefore, reduced the g value.

Two pans were constructed, but the low rear lip of the first pan left a poor finish and was used for only 16 slabs:



The second pan was similarly constructed but better adapted to the weight of the vibrators which were on hand:

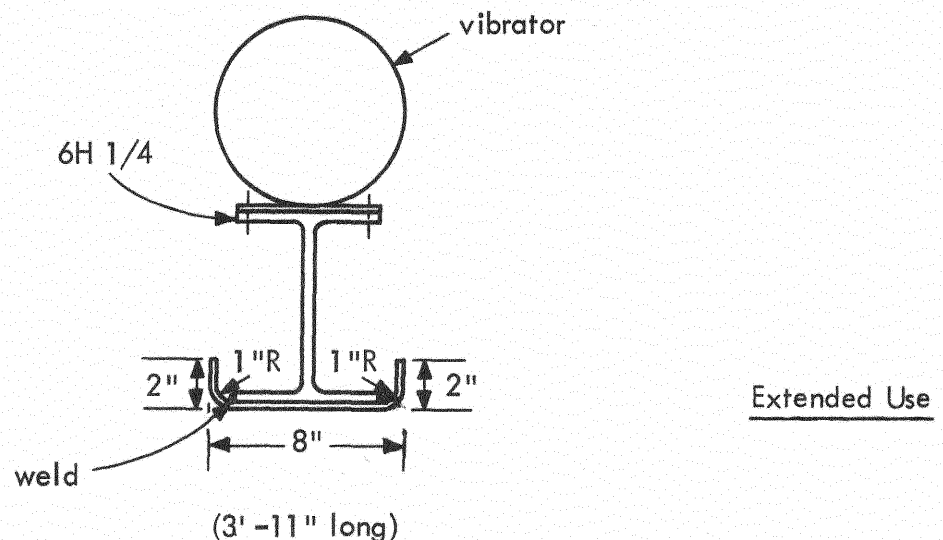


Table 2
Vibrator Characteristics

Designation	Weight of vibrator lbs.	Weight of pan lbs.	Weight of rotor lbs.	Eccentric distance in.	Amplitude in.	Rated frequency rpm	Acceleration (at rated rpm) g
VI	18.5	60.6	0.922	0.532	0.0061	4,000	2.7
V2	18.5	60.6	0.922	0.532	0.0061	6,000	6.2
B1	60.5	124.25	2.26	0.49	0.0059	10,800	19.5
B2	47.5	124.25	8.31	0.55	0.0254	3,600	9.29
B3	55.5	124.25	11.82	0.59	0.0364	2,000	4.11
K1	113.25	124.25	7.78	0.38	0.012	4,600	7.17
K2	80.75	124.25	7.78	0.38	0.014	4,800	9.10
KM	62.75	124.25	2.43	0.41	0.0053	9,000	12.4

The support system for the pan was flexible to permit the floating pan to seek its own level within a 2 inch vertical limit. As shown in Figure 4 the carriage for the pan rode on the form edge and had a hand lift device to entirely raise the pan and vibrator above the concrete surface. The additional consolidation which usually took place allowed the pan to ride slightly below the original level by as much as 1/4 inch. In addition to permitting vertical movement, the flexible connections also damped vibrations which would otherwise have caused a vibration input through the carriage into the forms.

Determination of actual pan frequency and amplitude was taken during the process of revibration using a reed vibrometer (see Figure 5), and a hand amplitude meter.

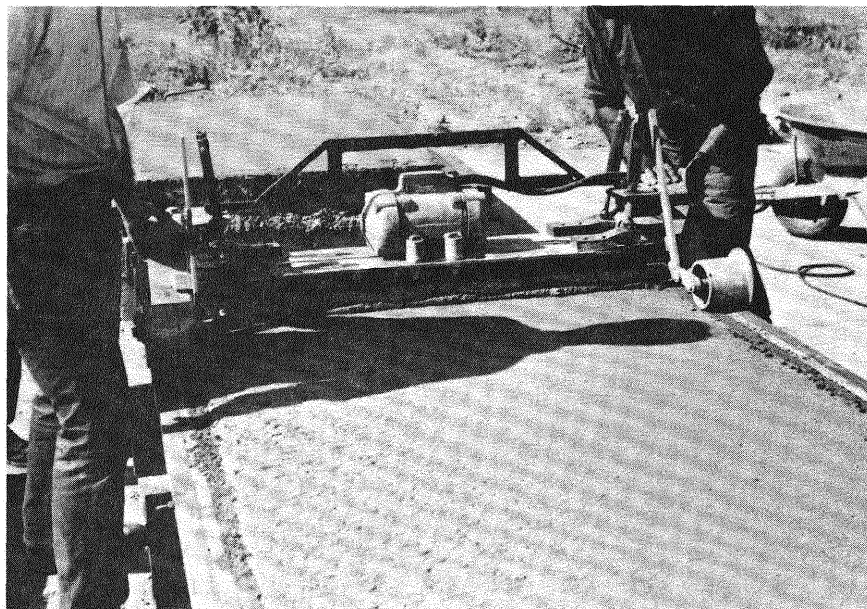


Figure 4 a. Carriage and Pan Viewed From the Front Side.

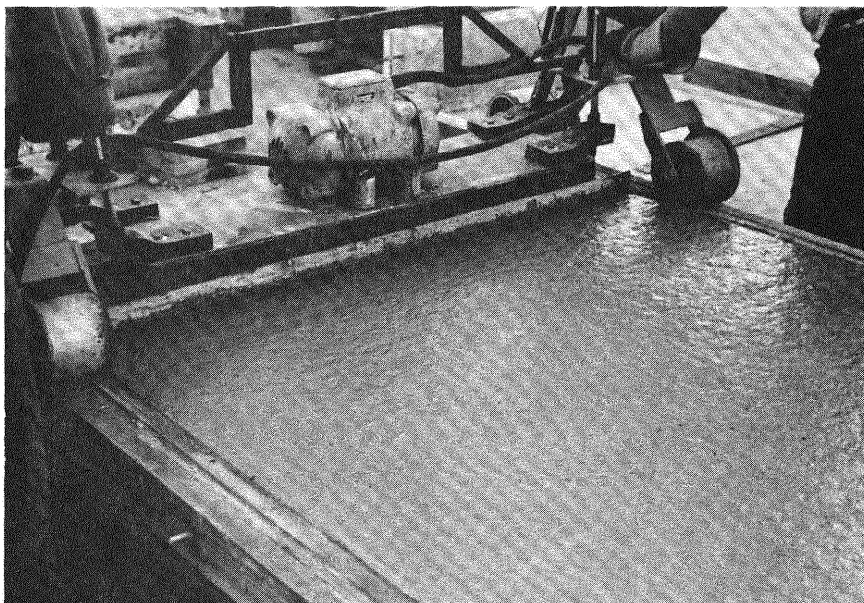


Figure 4 b. Carriage and Pan Viewed From the Rear.

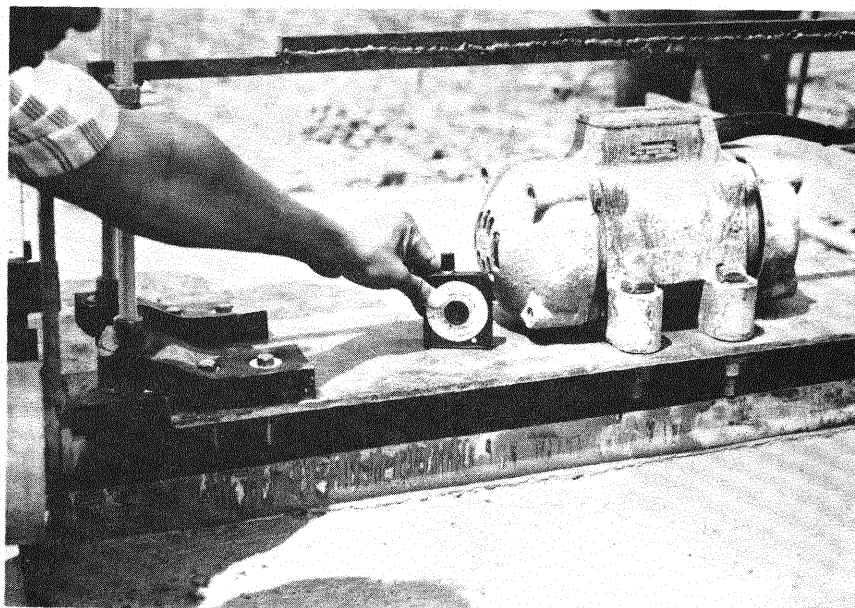


Figure 5 a. Measurement of Frequency and Amplitude of Vibration With a Reed Vibrometer and Amplidometer.

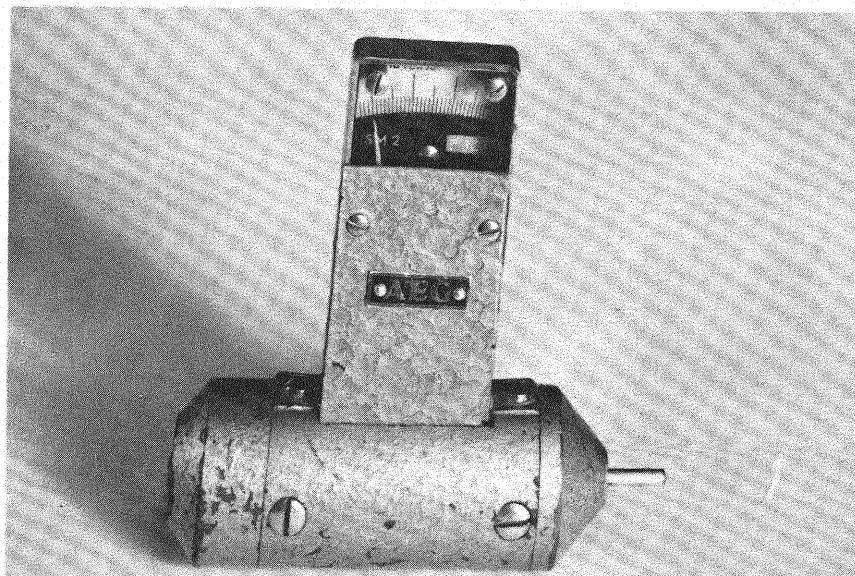


Figure 5 b. Amplidometer.

CHAPTER 3

EFFECTS OF SURFACE REVIBRATION

3.1 General

It was apparent at the outset that some latitude in vibrator frequency and amplitude was necessary to optimize results. Kirkham* has shown that surface vibration is a practical means of consolidating fresh concrete and documents data giving the distribution of vibration energy through the fresh mass in terms of slab thickness and vibrator frequency and amplitude. Previous surface revibration studies were limited to 2 levels of centrifugal force (a term which is not nearly so simple a function relative to the concrete vibrator or its effect as is generally believed, and the expression of its academic quantity with regards to specifications and results is of little or misleading value).

While it is possible to obtain a smooth surface with high frequency and low amplitude, the transfer of energy over a greater depth into the slab is achieved with high amplitude and low frequency vibration. The latter is very effective in achieving the desired consolidation inside the mass rather than on the surface. It is apparent that the resulting surface finish will not be as smooth as with the former. The centrifugal force of the vibrator is proportional to the square of the frequency and its eccentricity. From the foregoing discussion, it becomes evident that for more or less the same amount of centrifugal force, two different characteristics may result in the surface finish of the slab depending on the frequency and eccentricity employed in the process. Hence a criterion based on the frequency and amplitude of the vibration appears more logical than the centrifugal force for selecting the energy levels for revibration of the bridge decks.

*R.H.H. Kirkham, "Compaction of Concrete by Surface Vibration," Proc. Budapest Conf., 1963.

Bridge deck deterioration is mainly due to the cracks formed on the surface in fresh concrete at the time of casting. They occur primarily because of the resistance offered by the reinforcement to the subsidence of concrete, excess bleeding and shrinkage caused by low humidity, high temperature and wind conditions.

Further deterioration is caused ultimately by the corrosion of the reinforcement by the chlorides entering through the fissures and by the freezing of the water accumulated in the cracks during cold weather. Thus it is obvious that the deterioration of the bridge decks is primarily a function of the soundness of the top few inches of the deck.

The primary problem then is to reliquify the partially set mass, in order to permit additional consolidation occasioned by loss of water due to evaporation, absorption, bleeding, and hydration and to simultaneously close drying shrinkage, subsistence, and deflection cracks. In addition to reliquifying the paste, one must also leave a smooth and easily finished surface behind the vibrating pan, but not an overpasted surface or overworked with the resulting loss of entrained air.

In order to obtain an optimal frequency and nominal amplitude suitable for field revibration, 8 different vibrators giving a frequency range of 2000 to 10,800 cpm and nominal amplitudes varying from 0.00592 to 0.036 inches were used.

3.2 Elimination of Cracking by Revibration

Repeating those same variables in a random manner used in the production of the control slabs, 118 surface revibrated slabs were cast, with the time of revibration primarily a function of the penetration resistance of concrete. Tables 3, 4, and 5 summarily present this data.

Table 3
Details of Surface Revibrated Slabs

Slab Type & Number	Vibrating System	Time After Casting hr:min	Penetration Resistance psi	Travel Speed fpm	Surface Appearance after revibration	Cracking	
						Before revib.	After revib.
RVS-1	V	1:40	25	8		yes	yes
RVS-2	V	2:05	50	8	sandy, rough textured	yes	yes
RVS-3	V	2:00	99	8	sandy, rough textured	yes	yes
RVS-4	V	2:12	200	8	rough textured	yes	yes
RVS-5	B1	2:31	25	8	undulating	yes	
RVS-6	B1	3:10	50	8	slightly undulating	yes	
RVS-7	B1	3:34	100	8		yes	
RVS-8	B1	4:05	200	8	rough textured	yes	yes
RVS-9	B1	2:12	36	4	smooth	yes	
RVS-10	B1	2:16	55	2.1	excess paste accumulation	yes	yes
RVS-11	B1	2:41	105	2.7	smooth	yes	
RVS-12	B1	2:59	200	2.7	smooth	yes	
RVS-13	B1	1:00	30	4	smooth		
RVS-14	B1	1:24	65	5	smooth		
RVS-15	B1	1:30	130	2	smooth		
RVS-16	B1	1:54	200	1	undulating		
RVS-17	B1	2:20	160	1.3	undulating		
RVS-18	B1	2:05	120	1.5	smooth		
RVS-19	B1	1:50	65	3.75	smooth		
RVS-20	B1	1:35	30	5.3	smooth		
RVS-21	B2	2:30	30	2	air voids		
RVS-22	B2	3:00	60	2.2	air voids; undulating		
RVS-25	B2	2:35	35	3.7	smooth		
RVS-26	B2	3:30	90	1	smooth		
RVS-27	B2	3:40	108	1	smooth		
RVS-29	B2	3:30	30	3	smooth		
RVS-30	B3	6:00	70	1.5	smooth		
RVS-33	B3	3:30	32	1.6	smooth		
RVS-34	B3	5:30	70	1.7	undulating		
RVS-37	B1	3:10	32	6	undulating		
RVS-38	B1	3:40	62	5.4	smooth		
RVS-39	B1	4:05	90	8	air voids		
RVS-41	K1	3:11	32	5.5	sandy, rough textured		
RVS-42	K1	3:52	65	10.6	rough textured		
RVS-43	K1	3:48	90	7.3	undulating		
RVS-44	K1	4:16	140	5.3	undulating		
RVS-45	B3	2:46	30	5.3	poor		
RVS-46	B3	3:14	60	5	poor		
RVS-47	B3	3:19	90	6	poor		
RVS-48	B3	3:55	140	4	poor		
RVS-49	B2	2:46	30	5.3	smooth		
RVS-50	B2	3:10	60	4.3	smooth		
RVS-51	B2	3:30	95	2.2	smooth		
RVS-52	B2	3:46	130	3.5	smooth		
RVS-53	B2	3:13	30	5.3	smooth	yes	
RVS-54	B2	3:23	65	8	smooth	yes	
RVS-55	B2	3:38	100	4.5	smooth	yes	
RVS-56	B2	3:48	120	5	smooth	yes	
RVS-57	B3	3:18	30	8	smooth	yes	
RVS-58	B3	3:28	60	5	undulations	yes	yes
RVS-59	B3	3:48	120	5	rough textured	yes	
RVS-61	K2	6:00	28	4	moderately smooth	crusting	
RVS-62	KM	6:50	65	2	rough	crusting	
RVS-63	KM	7:10	95	2	rough	crusting	
RVS-64	KM	7:20	120	3	rough	crusting	
RVS-67	K2	6:35	55	4	moderately smooth		
RVS-68	K2	6:00	30	6	moderately smooth		

Table 3 (continued)

Slab Type & Number	Vibrating System	Time After Casting hr:min	Penetration Resistance psi	Travel Speed fpm	Surface Appearance after revibration	Cracking	
						Before revib.	After revib.
RVS-69	B1	0:50	30	5	rough textured		
RVS-70	B1	1:20	60	4	smooth		
RVS-71	B1	1:50	110	3.1	excess paste		
RVS-72	B1	1:55	206	2.6	rough textured		
RVS-75	B1	1:30	34	2.8	undulating		
RVS-76	B1	1:30	34	6.5	smooth		
RVS-77	B1		30	5.6	smooth		
RVS-81	B1	1:45	15	4.3	smooth		
RVS-82	B1	2:00	30	6.6	smooth		
RVS-83	B1	2:10	45				
RVS-84	B1	2:20	45	4			
RVS-85	B1	1:35	35	6.8	smooth	yes	yes
RVS-86	B1	1:47	70	4.35	smooth	yes	
RVS-87	B1	2:03	150	3.33	smooth	yes	
RVS-89	B1	2:20	30	8	smooth	yes	yes
RVS-90	B1	2:28	42	7.8	smooth	yes	yes
RVS-91	B1	2:38	58	7.8	smooth	yes	
RVS-92	B1	2:45	120	7.8	air voids	yes	
RVS-93	B1	2:15	30	4	smooth	yes	
RVS-94	B1	2:22	60	4	smooth	yes	yes
RVS-95	B1	2:39	70	4	smooth	yes	yes
RVS-96	B1	2:40	110	4	smooth	yes	
RVS-97	B3	2:25	20	6.3	smooth		
RVS-98	B3	3:05	40	7.5	smooth		
RVS-99	B3	3:20	60	5.0	smooth		
RVS-100	B3	1:30	8	9.9	smooth		
RVS-102	B3	2:13	15	8.1	smooth		
RVSR-1	B1	3:03	30	2.6	rough textured	yes	
RVSR-2	B1	3:15	60	3.2	rough textured	yes	
RVSR-3	B1	3:15	100	3.2	rough textured	yes	
RVSR-4	B1	2:45	20	2.2	smooth		
RVSR-5	B1	2:57	40	3.6	rough textured		
RVSR-6	B1	3:07	22	3	smooth	yes	
RVSR-7	B1	3:30	55	2.6	sandy, crusty surface	yes	
RVSR-8	B1	4:00	100	2.2	rough textured		yes
RVSR-9	B1	3:28	23	2.4	undulating, rough	yes	
RVSR-10	B1	3:38	23	2.6	undulating, rough		
RVSR-11	B1	3:50	82	4.0	undulating, rough		
RVSR-12	B1	2:40	10	3.5	rough	yes	yes
RVSR-13	B1	3:05	18	2.6	rough textured	yes	
RVSR-14	B1	3:20	18	2.5	rough textured	yes	yes
RVSR-15	B1	3:57	18	3.3	rough textured	yes	yes
RVSR-16	B1	2:55	70	3.2	smooth	yes	
RVSR-17	B1	3:05	100	2.6	smooth	yes	yes
RVSR-18	B1	3:10	110	2.6	smooth		
RVSR-19	B1	2:45	22	4.0	smooth		
RVSR-20	B1	3:00	40	2.6	smooth		yes
RVSR-21	B1	3:20	80	2.8	smooth		yes
RVSR-22	B1	1:48	15	2.6	smooth		
RVSR-23	B1	1:56	26	2.6	rough textured		
RVSR-24	B1	2:04	80	2.6	rough textured		
RVSR-25	B1	4:05	10	5.7	smooth	yes	
RVSR-26	B1	4:35	20	6.0	smooth	yes	yes
RVSR-27	B1	4:30	15	6.4	smooth	yes	yes

Table 3 (continued)

Slab Type & Number	Vibrating System	Time After Casting hr:min	Penetration Resistance psi	Travel Speed fpm	Surface Appearance after revibration	Cracking	
						Before revib.	After revib.
RVSR-28	B1	4:00	5	5.3	smooth		
RVSR-29	B1	4:05	8	4.6	smooth		
RVSR-30	B1	4:10	10	8	smooth		
RVSR-31	B1	2:51	15	2.6	smooth	yes	yes
RVSR-32	B1	2:55	20	2.2	smooth		
RVSR-33	B1	3:20	45	4.0	smooth		
RVSR-34	B1	2:45	7	6.0	smooth		

Table 4
Classification of Cracks in Control Slabs. (Defective)

Slab type and Number	W/C	Cover on top reinforcement in.	Maximum positive defl. in.	Cracking				Surface deterioration
				Type	Extent	Max. crack width in.	Av. crack length in.	
DS-1	0.6	1.0	NA	transverse	medium	0.015	5	light flaking
DS-2	0.6	0.75	0.30	-	-	-	-	light flaking
DS-3	0.6	0.75	0.45	transverse	slight	0.003	4	light flaking
DS-4	0.6	0.75	0.44	transverse	slight	0.005	3	light flaking
DS-5	0.6	0.75	0.53	-	-	-	-	light flaking
DS-6	0.68	0.75	0.42	long.	severe	0.020	3	light flaking
DS-7	0.68	0.75	0.30	transverse	severe	0.04	36	-
DS-8	0.68	0.5	0.52	transverse	medium	0.03	7	light flaking
DS-9	0.68	0.5	0.07	long.	medium	0.009	60	light flaking
DS-10	0.68	0.75	0.23	long.	slight	0.015	60	heavy flaking
DS-11	0.68	no reinforcement	-	transverse	medium	0.04	9	air voids
DS-12	0.45	0.5	0.4	transverse	slight	0.01	3	light flaking
DS-13	0.45	0.5	0.32	random	slight	0.006	2	light flaking
DS-14	0.45	no reinforcement	-	random	slight	0.007	2	heavy flaking
DS-15	0.68	0.5	0.26	transverse	slight	0.015	6	scaling
DS-16	0.68	0.5	0.29	transverse & long.	medium	0.02	6	scaling
DS-17	0.68	0.5	0.27	transverse	medium	0.03	8	heavy flaking
DS-20	0.48	1.25	0.26	-	-	-	-	light flaking
DS-21	0.48	1.5	0.2	-	-	-	-	-
DS-22	0.48	1.5	0.48	-	-	-	-	-
DS-23	0.48	1.0	0.25	-	-	-	-	-
DS-24	0.84	1.5	0.24	-	-	-	-	light flaking
DS-25	0.84	0.5	0.25	-	-	-	-	light flaking
DS-26	0.84	0.5	0.40	-	-	-	-	light flaking
DS-27	0.84	1.5	0.28	-	-	-	-	light flaking
DS-28	0.42	1.5	0.17	-	-	-	-	-
DS-29	0.42	1.0	0.24	-	-	-	-	light flaking
DS-30	0.42	1.25	0.39	-	-	-	-	-
DS-31	0.42	1.5	0.19	-	-	-	-	-
DS-32	0.62	1.75	0.19	-	-	-	-	light flaking
DS-33	0.73	1.75	0.22	transverse	medium	0.015	4	light flaking
DS-34	0.73	0.5	0.18	transverse & long.	severe	0.020	4	-
DS-35	0.73	0.5	0.26	transverse & long.	severe	0.020	6	-
DS-36	0.59	1.5	0.15	-	-	-	-	light flaking
DS-37	0.59	1.5	0.16	-	-	-	-	light flaking
DS-38	0.59	0.5	0.37	long. & pattern	medium	0.025	5	-
DS-39	0.59	0.5	0.19	long. & pattern	slight	0.015	3	-
DS-40	0.4	1.5	0.26	-	-	-	-	light flaking
DS-41	0.4	1.5	0.22	-	-	-	-	-
DS-42	0.4	0.5	0.22	long.	slight	0.009	18	light flaking
DS-43	0.4	0.5	0.22	long.	slight	0.003	3	light flaking
DS-44	0.61	0.5	0.28	-	-	-	-	light flaking
DS-45	0.61	0.5	0.27	-	-	-	-	light flaking
DS-46	0.61	1.5	0.17	long.	slight	0.003	2	light flaking
DS-47	0.61	0.5	0.17	-	-	-	-	light flaking
DS-48	0.47	1.5	0.19	transverse	medium	0.015	3	heavy flaking
DS-49	0.47	1.5	0.22	transverse & long.	severe	0.12	6	heavy flaking
DS-50	0.47	0.5	0.32	transverse & long.	severe	0.08	9	-
DS-51	0.47	0.5	0.24	transverse & long.	severe	0.12	6	-
DS-52	0.77	1.5	0.26	random	slight	0.010	-	heavy flaking
DS-53	0.77	1.5	0.26	long.	slight	0.020	4	heavy flaking

Table 4 (Continued)

Slab type and Number	W/C	Cover on top reinforcement in.	Maximum positive defl. in.	Cracking				Surface deterioration
				Type	Extent	Max. crack width in.	Av. crack length in.	
DS-54	0.77	0.5	0.28	transverse & long.	medium	0.020	7	heavy flaking
DS-55	0.77	0.5	0.28	long.	medium	0.030	12	-
DS-56	0.61	0.5	0.14	-	-	-	-	-
DS-57	0.61	1.5	0.24	-	-	-	-	-
DS-58	0.61	1.5	readings	-	-	-	-	-
DS-59	0.59	0.5	not	-	-	-	-	light flaking
DS-60	0.59	1.5	taken	-	-	-	-	light flaking
DS-61	0.59	0.5	after	-	-	-	-	light flaking
DS-62	0.59	1.5	DS-57	-	-	-	-	light flaking
DS-64	0.55	1.5		long. & transverse	slight	0.035	12	-
DS-65	0.49	0.5		-	-	-	-	-
DS-66	0.49	1.5		-	-	-	-	light flaking
DS-67	0.41	1.5		-	-	-	-	light flaking
DS-68	0.41	1.5		-	-	-	-	-
DS-69	0.43	1.5		-	-	-	-	-
DS-70	0.43	1.5		-	-	-	-	-
DS-71	0.43	1.5		-	-	-	-	-
DS-72	0.55	0.5		long.	medium	0.025	12	-
DS-73	0.55	1.5		-	-	-	-	-
DS-74	0.55	0.5		-	-	-	-	-
DS-75	0.55	1.5		long.	medium	0.025	7	-
DS-76	0.54	0.5		-	-	-	-	-
DS-77	0.54	1.5		-	-	-	-	light flaking
DS-78	0.54	0.5		-	-	-	-	-
DS-79	0.54	1.5		-	-	-	-	-
DS-80	0.70	1.5		-	-	-	-	-
DS-81	0.60	0.5		long.	slight	0.02	6	-
DSR-1	0.43	0.5		long.	medium	.04	6	-
DSR-2	0.41	0.5		long.	slight	.007	3	light flaking
DSR-3	0.41	1.5		-	-	-	-	-
DSR-4	0.43	1.5		-	-	-	-	-
DSR-5	0.48	0.5		-	-	-	-	-
DSR-6	0.65	0.5		-	-	-	-	-
DSR-7	0.7	0.5		-	-	-	-	-
DSR-8	0.65	0.5		-	-	-	-	-
DSR-9	0.70	0.5		-	-	-	-	-
DSR-10	0.70	1.5		long.	slight	0.015	4	-
DSR-11	0.70	0.5		long.	slight	0.015	6	-
DSR-12	0.70	1.5		long.	slight	0.015	6	-
DSR-13	0.75	1.5		-	-	-	-	light flaking
DSR-14	0.66	1.5		long. & transverse	slight	0.02	4	-
DSR-15	0.47	1.5		random	slight	0.01	2	-
DSR-16	0.60	1.5		-	-	-	-	-

Table 5
Classification of Cracking in Revibrated Slabs

Slab Type and Number	Water-Cement Ratio	Mid-span defl. of loaded form in.	Cover on top reinforcement in.	Pre-revibration cracking	Post-revibration cracking				Surface Deterioration
					Type	Extent	Maximum crack width in.	Average crack length in.	
RVS - 1	0.77	0.23	0.5	yes	random		0.02		light flaking
RVS - 2	0.77	0.38	0.5	yes	transverse	severe	0.02		-
RVS - 3	0.77	0.25	1.5	yes	transverse	severe	0.025		light flaking
RVS - 4	0.77	0.36	0.5	yes	transverse		0.02		light flaking
RVS - 5	0.67	0.23	1.5	yes	-	-	-	-	light flaking
RVS - 6	0.67	0.26	1.0	yes	-	-	-	-	light flaking
RVS - 7	0.67	0.28	0.5	yes	-	-	-	-	-
RVS - 8	0.67	0.28	0.5	yes	transverse	medium	0.02	3	light flaking
RVS - 9	0.66	0.24	0.5	yes	-	-	-	-	-
RVS - 10	0.66	0.28	1.5	yes	-	-	-	-	light flaking
RVS - 11	0.66	0.29	1.5	yes	-	-	-	-	-
RVS - 12	0.66	0.25	0.5	yes	-	-	-	-	light flaking
RVS - 13	0.55	0.19	0.5	-	-	-	-	-	-
RVS - 14	0.55	0.32	1.5	-	-	-	-	-	-
RVS - 15	0.55	0.24	1.0	-	-	-	-	-	-
RVS - 16	0.55	0.23	1.0	-	-	-	-	-	-
RVS - 17	0.39	0.22	0.5	-	-	-	-	-	-
RVS - 18	0.39	0.35	1.0	-	-	-	-	-	-
RVS - 19	0.39	0.36	1.0	-	-	-	-	-	-
RVS - 20	0.39	0.32	1.0	-	-	-	-	-	-
RVS - 21	0.61	0.12	0.5	-	-	-	-	-	light flaking
RVS - 22	0.61	0.16	1.5	-	-	-	-	-	light flaking
RVS - 25	0.61	readings not taken after RVS-22	0.5	-	-	-	-	-	light flaking
RVS - 26	0.61		1.5	-	-	-	-	-	light flaking
RVS - 27	0.61		0.5	-	-	-	-	-	light flaking
RVS - 29	0.59		1.0	-	-	-	-	-	-
RVS - 30	0.59		1.5	-	-	-	-	-	light flaking
RVS - 33	0.59		0.5	-	-	-	-	-	light flaking
RVS - 34	0.59		1.5	-	random	slight			light flaking
RVS - 37	0.70		0.5	-	-	-	-	-	light flaking
RVS - 38	0.70		1.5	-	-	-	-	-	light flaking
RVS - 39	0.70		1.5	-	-	-	-	-	light flaking
RVS - 41	0.70		0.5	-	-	-	-	-	-
RVS - 42	0.70		1.5	-	-	-	-	-	-

Table 5 (Continued)

Slab Type and Number	Water-Cement Ratio	Mid-span defl. of loaded form in.	Cover on top reinforcement in.	Pre-revibration cracking	Post-revibration cracking				Surface Deterioration
					Type	Extent	Maximum crack width in.	Average crack length in.	
RVS - 43	0.70		1.5	-	-	-	-	-	-
RVS - 44	0.70		0.5	-	-	-	-	-	-
RVS - 45	0.41		0.5	-	-	-	-	-	-
RVS - 46	0.41		1.5	-	-	-	-	-	-
RVS - 47	0.41		0.5	-	-	-	-	-	-
RVS - 48	0.41		1.0	-	-	-	-	-	-
RVS - 49	0.41		0.5	-	-	-	-	-	-
RVS - 50	0.41		1.5	-	-	-	-	-	-
RVS - 51	0.41		0.5	-	-	-	-	-	-
RVS - 52	0.41		1.5	-	-	-	-	-	-
RVS - 53	0.55		0.5	yes	-	-	-	-	-
RVS - 54	0.55		1.5	yes	-	-	-	-	-
RVS - 55	0.55		0.5	yes	-	-	-	-	-
RVS - 56	0.55		1.5	yes	-	-	-	-	-
RVS - 57	0.55		0.5	yes	-	-	-	-	-
RVS - 58	0.55		1.5	yes	transverse	slight	0.015	-	-
RVS - 59	0.55		0.5	yes	-	-	-	-	-
RVS - 61	0.49		0.5	-	-	-	-	-	light flaking
RVS - 62	0.49		1.5	-	-	-	-	-	light flaking
RVS - 63	0.49								light flaking
RVS - 64	0.49		1.5	-	-	-	-	-	heavy flaking
RVS - 67	0.49		1.5	-	-	-	-	-	heavy flaking
RVS - 68	0.49		0.5	-	-	-	-	-	-
RVS - 69	0.55		1.5	-	-	-	-	-	-
RVS - 70	0.55		1.5	-	-	-	-	-	light flaking
RVS - 71	0.55		1.5	-	-	-	-	-	-
RVS - 72	0.55		1.5	-	-	-	-	-	-
RVS - 75	0.41		1.5	-	-	-	-	-	-
RVS - 76	0.41		1.5	-	-	-	-	-	-
RVS - 77	0.43		1.5	-	-	-	-	-	light crazing
RVS - 81	0.56		1.5	-	-	-	-	-	-
RVS - 82	0.56		1.5	-	-	-	-	-	-
RVS - 83	0.56		1.5	-	-	-	-	-	-
RVS - 84	0.56		1.5	-	-	-	-	-	-
RVS - 85	0.43		1.5	yes	transverse	-	0.015	-	-
RVS - 86	0.43		0.5	yes	-	-	-	-	-
RVS - 87	0.43		0.5	yes	-	-	-	-	-
RVS - 89	0.70		0.5	yes	long. & trans.	-	0.02	-	-

Table 5 (Continued)

Slab Type and Number	Water-Cement Ratio	Mid-span defl. of loaded form in.	Cover on top reinforcement in.	Pre-revibration cracking	Post-revibration cracking				Surface Deterioration
					Type	Extent	Maximum crack width in.	Average crack length in.	
RVS - 90	0.70		1.5	yes					
RVS - 91	0.70		0.5	yes	-	-	-	-	-
RVS - 92	0.70		1.75	yes	-	-	-	-	-
RVS - 93	0.80		0.5	yes	-	-	-	-	light flaking
RVS - 94	0.80		1.5	yes	trans. & long.	slight	0.025	2	-
RVS - 95	0.80		0.5	yes	trans. & long.		0.03		-
RVS - 96	0.80		1.5	yes	-	-	-	-	-
RVS - 97	0.70		0.5	-	-	-	-	-	-
RVS - 98	0.70		0.5	-	-	-	-	-	-
RVS - 99	0.70		1.5	-	-	-	-	-	light flaking
RVS - 100	0.60		1.5	-	-	-	-	-	-
RVS - 102	0.60		1.5	-	-	-	-	-	-
RVSR - 1	0.43		1.5	yes	-	-	-	-	-
RVSR - 2	0.43		0.5	yes	-	-	-	-	-
RVSR - 3	0.43		1.5	yes	-	-	-	-	-
RVSR - 4	0.41		1.5	-	-	-	-	-	light flaking
RVSR - 5	0.41		0.5	-	-	-	-	-	-
RVSR - 6	0.43		0.5	yes	-	-	-	-	scaling
RVSR - 7	0.43		0.5	yes	-	-	-	-	-
RVSR - 8	0.43		1.5	-	transverse	slight	-	-	crazing
RVSR - 9	0.48		1.5	yes	-	-	-	-	-
RVSR - 10	0.48		1.5	-	-	-	-	-	-
RVSR - 11	0.48		0.5	-	-	-	-	-	-
RVSR - 12	0.53		0.5	yes	long.	slight	-	-	-
RVSR - 13	0.53		1.5	yes	-	-	-	-	-
RVSR - 14	0.53		0.5	yes	long. & trans.	slight	0.035	4.0	-
RVSR - 15	0.53		1.5	yes	trans.	slight	0.015	1.5	-
RVSR - 16	0.65		1.5	yes	-	-	-	-	light flaking
RVSR - 17	0.65		0.5	yes	pattern	slight	.003	3.0	-
RVSR - 18	0.65		1.5	-	-	-	-	-	-
RVSR - 19	0.7		1.5	-	-	-	-	-	-
RVSR - 20	0.7		0.5	-	pattern	slight	-	-	-
RVSR - 21	0.7		1.5	-	pattern	slight	-	-	-
RVSR - 22	0.65		1.5	-	-	-	-	-	-
RVSR - 23	0.65		0.5	-	-	-	-	-	-
RVSR - 24	0.65		1.5	-	-	-	-	-	-
RVSR - 25	0.75		1.5	yes	-	-	-	-	scaling
RVSR - 26	0.75		0.5	yes	trans. & long.	severe	0.02	5.0	-

Table 5 (Continued)

Slab Type and Number	Water-Cement Ratio	Mid-span defl. of loaded form in.	Cover on top reinforcement in.	Pre-revibration cracking	Post-revibration cracking				
					Type	Extent	Maximum crack width in.	Average crack length in.	Surface Deterioration
RVSR - 27	0.75		1.5	yes	trans.	-	-	-	-
RVSR - 28	0.66		0.5	-	-	-	-	-	-
RVSR - 29	0.66		0.5	-	-	-	-	-	-
RVSR - 30	0.66		1.5	-	pattern	slight	.003	1	-
RVSR - 31	0.47		0.5	yes	-	-	-	-	-
RVSR - 32	0.47		0.5	-	-	-	-	-	-
RVSR - 33	0.47		1.5	-	-	-	-	-	light flaking
RVSR - 34	0.60		1.0						

The problem of cracking begins as soon as the concrete has set for a brief time. Shrinkage cracking is often witnessed before finishing begins, and was frequently the case in this project, as may be seen in Figure 6 which also shows chronologically the results of effort on slab RVS.⁹¹

A most dramatic reduction in all forms of cracking is presented in Table 6, in terms of cover thickness over top reinforcing bars and water-cement ratios. Many other factors enter into consideration of causes of cracking but these two, cover and W/C, appear to be most significant in revealing the influence of surface revibration. Discussions concerning weather, curing conditions, penetration resistance, and vibrator characteristics hereafter will complete the picture. With a total of 212 slabs cast, 94 control and 118 revibrated, a decrease in the overall percentage of defective slabs from 47% to 17%, a 65% reduction, is noted.

3.2.1 Effects of Retarder

The influence of retarding the normal set of concrete was also studied in 2 series, DSR (control) and RVSR (revibrated). There was no apparent difference in the cracking rate of the control slabs but there is a noticeable difference in the relative reduction of cracking attributed to revibration, being only 37%, whereas those slabs without retarder showed a 75% decrease in cracking due to surface revibration. Apparently the additional drying time and the obvious crusting which was common to a large number of retarded slabs was not totally overcome by the surface revibration. There is, of course, a chemical variable which enters consideration but is not studied here.

Subsequent floating of the revibrated retarded slabs was sufficiently difficult that it would, in general, be impractical in the field unless the penetration resistance (P.R.) were less than 15 psi and crusting were minimal. Several typical P.R. vs. time graphs are reproduced in Figure 7. The usual 4 to 6 ounces of retarder per



Figure 6 a. Presence of Longitudinal Shrinkage Cracks Before Surface Revibration (RVS-91).

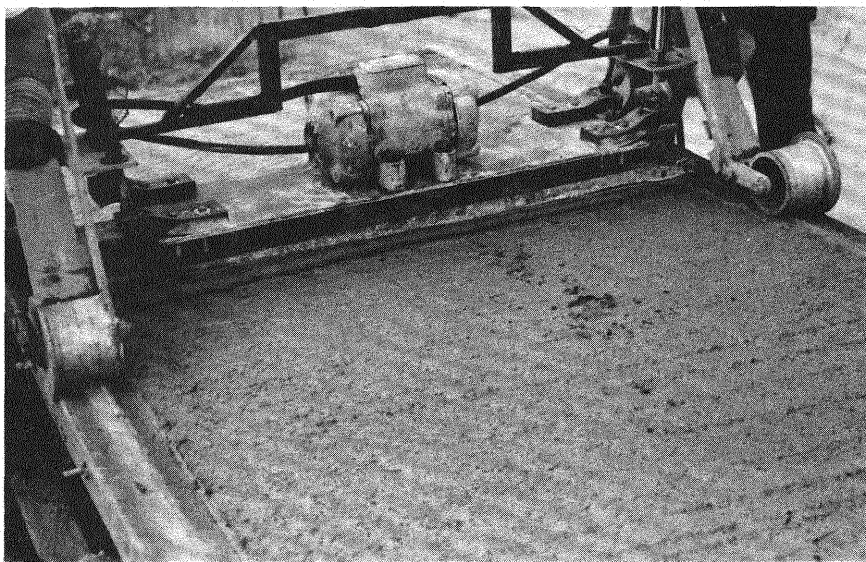


Figure 6 b. Surface Appearance Prior to Revibration (RVS-91).

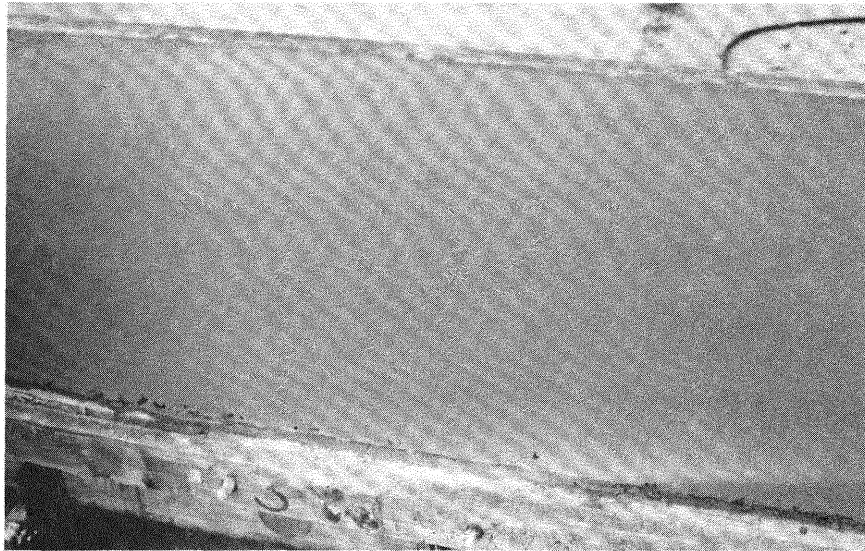


Figure 6 c. Surface Appearance After Revibration and 4 Passes of Bull Float (RVS-91).

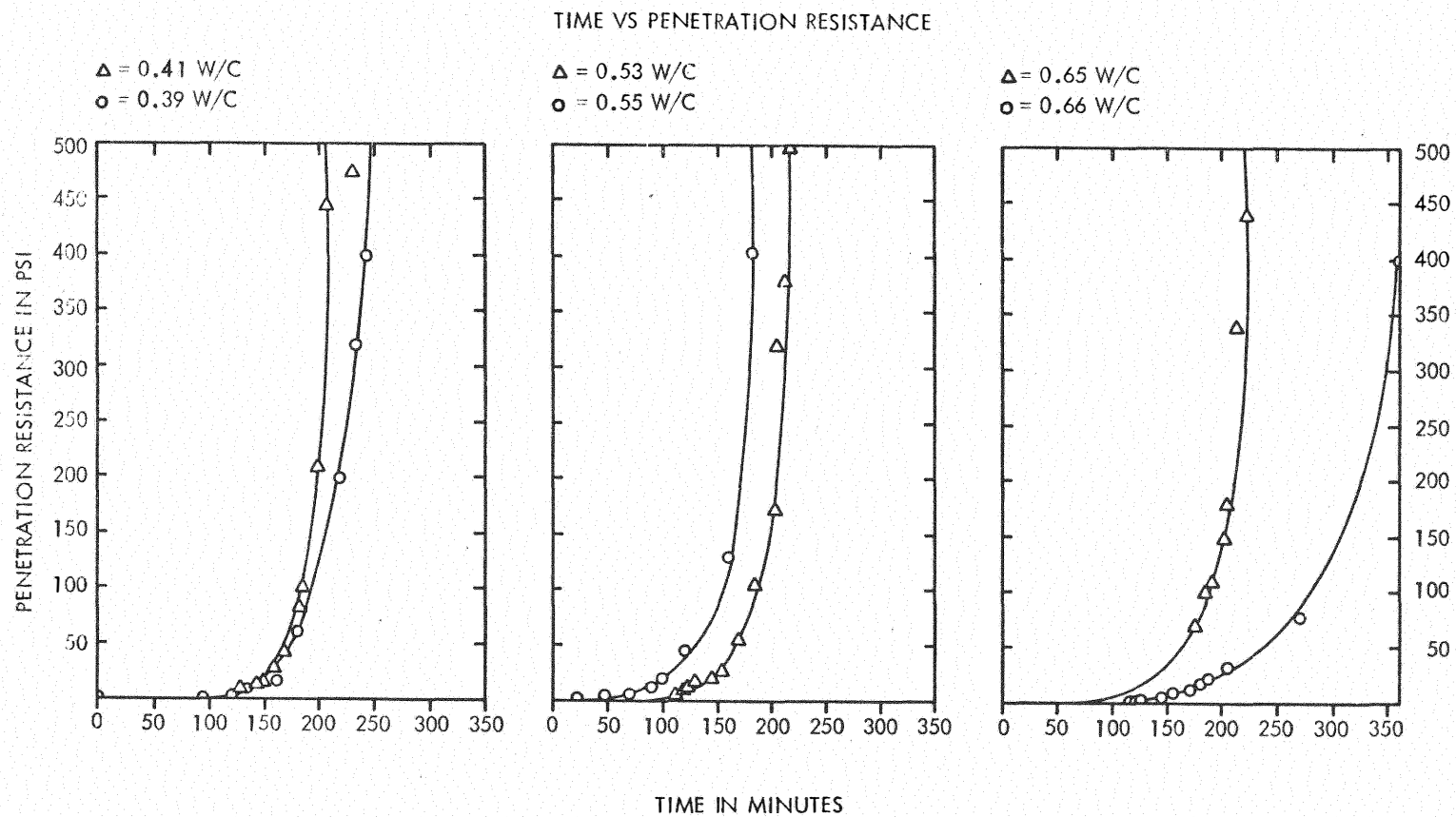


Figure 7. Typical P.R. vs. Time Graphs.

Table 6
Summary of Slab Cracking, Total

Depth of Cover (in)	Water- Cement ratio	No. Slabs Cast				No. and (%) of Slabs That Cracked			
		<u>Control</u>		<u>Revibrated</u>		<u>Control</u>		<u>Revibrated</u>	
		Plain	With retarder	Plain	With retarder	Plain	With retarder	Plain	With retarder
0.5 to 1.0	0.40	3	2	11	4	2(67)	2(100)	0	0
	0.475	6	1	3	3	5(71)	0	0	0
	0.55	4	0	7	2	1(25)	0	0	2(100)
	0.625	14	2	8	5	6(38)	0	0	1(20)
	0.70	10	3	8	2	10(100)	1(67)	2(25)	1(50)
	0.775	4	0	5	1	2(50)	0	3(60)	1(100)
1.25 to 1.75	0.40	10	2	7	4	1(8)	0	1(13)	1(25)
	0.475	7	1	3	3	3(43)	1(100)	0	0
	0.55	5	0	12	2	2(40)	0	1(8)	1(50)
	0.625	7	2	8	5	1(14)	1(50)	1(13)	1(20)
	0.70	4	2	8	2	2(50)	2(100)	0	1(50)
	0.775	4	1	3	2	2(40)	0	2(67)	1(50)
<u>Totals</u>		78	16	83	35	37(48%)	7(44%)	10(12%)	10(29%)
<u>Combined Totals</u>		94		118		44(47%)		20(17%)	

sack of cement are represented there, with no apparent consistency. Comparison with the weather data given in Table 11 helps to a limited degree.

3.2.2 Effect of Curing Agent

An emulsified linseed oil compound (OHD approved) was applied as a spray on a total of 33 slabs. Two points were intended by its use: first to observe the normal influence on cracking, and secondly, to observe any effects when used prior to surface revibration (for the purpose of reducing water loss and crusting).

The first point is summarized in Table 7. There is no apparent difference in the cracking rate of control and revibrated slabs which were cured.

Table 7
Cracking and Use of Curing Agent

	Control	Revibrated
Linseed Oil Cured	24	9
Those Above Which Cracked	5	2
Percentage	21%	22%

In the case of point two, it was found that when a normal application of linseed oil compound is applied prior to revibration that the intimate mixing of the oil and the top paste is detrimental to the hardening process of the surface. Surfaces which were treated in this manner remained soft (light hand or foot abrasion would scrape it loose down to about 1/16 inch) up to 1 1/2 years later.

3.2.3 Effects of Frequency and Amplitude

It was found that crack closure was primarily a function of reliquification and that any combination of frequency (n) and amplitude (a) which did this was effective in eliminating cracks. The secondary points then become of chief concern:

what kind of surface did the pan leave with the particular vibrator and/or levels of $\underline{n}$ and $\underline{a}$; is the pan weight such that full depth vibrations are transmitted (as a function of amplitude) and yet not so heavy as to be unwieldy with the carriage device used and tending to sink inordinately; is there a good finishing surface produced but not excessive paste?

Rather quick decisions were made concerning the continued use of a given vibrator once it had been tried. Upon the first use it was apparent whether or not the vibrator and or level of $\underline{n}$ and $\underline{a}$ were practical.

Vibrator performance is listed in Table 8, which rates vibrator B1 as best overall. However, those vibrators with slower frequencies would have been more acceptable if the pan and carriage were adequate for the weights involved. In general it can be reported that satisfactory crack closure and surface conditions can be produced with frequencies of 3600 to 10,000 cpm and accelerations between 4 and 20 g.

Table 8
Vibrator Performance

<u>Designation</u>	<u>Comments on Performance</u>
V1, 2	Transmits sufficient energy to reliquify mortar to a depth of 1 to 3 inches at penetration resistance (P.R.) less than 50 psi. Ineffective at high P.R. values. Frequency does not hold constant in contact with fresh concrete. Produces smooth surface but over-pasted. General rating: 1 <u>(4)</u> 10
B1	Reliquification energy to 8 inch depth at P.R. up to about 150 psi. Surface produced generally smooth and workable. Maintains frequency under all conditions herein. General rating: 1 <u>(8)</u> 10
B2	Excessive impact for this study - vibrated everything within about 8 ft. and concrete reliquified up to 6 ft. away from it. Surface is rough and difficult to finish, with large air pockets commonly found on surface. General rating: 1 <u>(6)</u> 10
B3	Works well in P.R. up to 80 psi, but depth of reliquification is limited. Does not maintain rated frequency in contact with fresh concrete, but does leave smooth surface. General rating: 1 <u>(4)</u> 10
K1	Too heavy for the pan used here; force output is sufficient to liquify concrete to full depth. General rating: 1 <u>(5)</u> 10
K2	Same as K1
KM	Handles poorly - too big and unmanageable for this project.

3.2.4 Penetration Resistance and Pan Travel Speed

Forward travel speed was adjusted to produce a visually "best" condition, taking into account depth of reliquification, surface pasting, surface smoothness and subsequent float finishing. Considering the foregoing, a satisfaction rating was given to the overall outcome and then graphed in relation to travel speed to find optimums at the various penetration resistances (P.R.). As one would expect, high P.R. required slower travel speeds. There was a rather wide variation in these optimum speeds but the guidelines of Table 9 may be of some value.

Table 9
Production of Satisfactory Surfaces as Related to
Travel Speed and Penetration Resistance

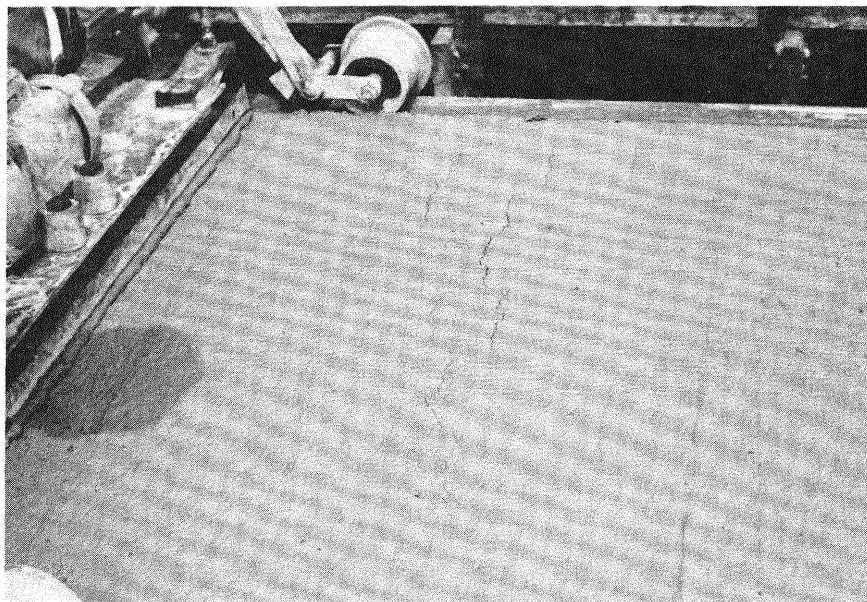
Penetration Resistance (psi)	Travel Speed (feet/minute)
0 to 20	5 to 9
20 to 40*	4 to 7*
40 to 70*	3 to 6*
70 to 100	2 to 5
100 to 200	1 to 3

*Overall best results occurred in this range

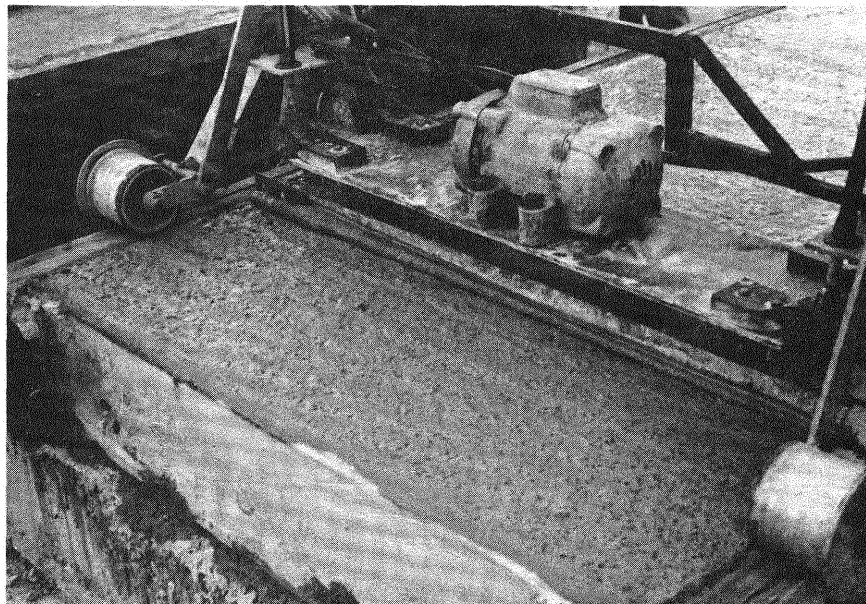
It was found that the best results were produced when a one to two inch roll of mortar was produced on the forward edge of the vibratory pan, indicating that total contact between pan and surface was being maintained (see Figure 8).

It has been observed that satisfactory results can be obtained with P.R. up to 200 psi, but the practical aspects of finishing the surface of concrete which is that far advanced in setting, even immediately after reliquification, reduces the likelihood of its use. In order to maximize the reduction of cracking and to increase other benefits such as strength, consolidation, etc., it is best to revibrate the highest practical P.R. The recommendations of this study are that revibration be performed between 20 and 60 psi P.R. and that care be taken not to permit time for crusting of the surface.

As a supplementary project, an alternate means of determining the P.R. in addition to the standard ASTM method, was reviewed. Two things became evident in the application of ASTM guidelines: one, sieving concrete through a No. 4 screen to obtain the mortar for use in determining P.R. was a task that would likely be inconvenient in the field, and two, the standard 6 inch metal container for the mortar does not consistently reflect the stiffness of the concrete in a slab.



(a)



(b)

Figure 8. Formation of Roll of Mortar at Optimum Travel Speed of Vibrating System.

As solutions to the above, a 3/8 inch sieve was tried which proved to be statistically consistent with the P.R. taken with the No. 4 sieved mortar. In addition, a one foot square wooden mold 8 inches deep (filled to 6 inches) and set along side the actual slabs (subject to same weather conditions) proved to be superior in accurately reflecting the stiffness of the slab concrete. It was also learned that with experience one could use his finger to estimate the P.R. of a concrete on the slab itself where use of a standard penetrometer is not feasible because of the large aggregate. On several occasions this hand touch check averted a situation of having the slab become too stiff to properly revibrate, even though the standard ASTM P.R. sample was still showing low values. Following several such experiences, the alternate method was developed and proved more satisfactory than did the standard method.

3.2.5 Effect of Concrete Cover Over Top Reinforcement

Control slabs reflect what has been known for some time, that the thinner the cover over top bars the greater the likelihood of cracking. There was 59% cracking of all control slabs (see Table 10) with cover less than 1.0 inch and only 30% cracking of those with a 1.25 inch cover or more.

Table 10
Cracking as Influenced by Depth of Cover
Over the Top Reinforcement

Depth of Cover (in)	No. Slabs Cast		No. and % That Cracked	
	Control	Revibrated	Control	Revibrated
0.5 to 1.0	49	59	29(59%)	10(17%)
1.25 to 1.75	43	60	13(30%)	10(17%)

It is apparent that surface revibration has removed the element of cover as it effects cracking in that the same percentage of cracking occurred in both depths of cover ranges. This, of course, has significant economic implications in minimizing slab thickness.

3.3 Weather

A complete review of the effects of revibration on the occurrence of cracking in slabs would be incomplete without considering the effects of weather. Unlike many other fields of concrete construction, bridge decks are very much open to and influenced by prevailing weather conditions at the time of casting and thereafter. Those conditions existing at the time of slab casting are tabulated in Table 11 along with a listing of freeze-thaw cycles since that time.

In general, it was noted that the problems of winter concreting were more severe than those of summer. The tendency to dry and crust was accentuated in the cold periods. The effects of wind were also more predominant than the effects of temperature. Since both control and revibrated slabs were cast in winter and summer, the overall effects are naturally averaged into the results and no attempt is made here to further delineate them.

Table 11
Weather Data (January, 1971 to June, 1973)
(Norman, Oklahoma)

Slab Type and Number	Weather at the time of casting			Temperature within 24 hrs. of casting		Number of freeze-thaw cycles	Number of wet freeze-thaw cycles
	Temp. °F	Humidity %	Ave. wind mph	Max. °F	Min. °F		
DS - 1	46	53	7.9	47	37	73	11
DS - 2 to 5	62	26	9.1	64	52	63	10
DS - 6 to 8	64	23	9.6	64	50	56	8
DS - 9 to 11	49	45	13.5	52	32*	55	8
DS - 12 to 14	74	42	16.7	76	52	55	8
DS - 15 to 17	73	25	20.9	78	48	53	8
DS - 20 to 23	85	50	14.2	86	67	53	8
DS - 24 to 27	93	37	10.6	96	68	53	8
DS - 28 to 31	83	51	10.8	86	68	53	8
DS - 32 to 35	91	46	10.8			53	8
DS - 36 to 39	77	60	11.1	82	65	53	8
DS - 40 to 43	86	52	7.8	86	62	53	8
DS - 44 to 47	88	42	6.6	90	66	53	8
DS - 48 to 51	89	37	7.1	90	69	53	8
DS - 52 to 55	76	86	7.5	78	56	53	8
DS - 56 to 58	52	99	12.8	52	33	45	5
DS - 59 to 62	45	65	18.8	48	12*	44	4
DS - 63	51	34	11.5	52	33	41	3
DS - 64	66	29	16.7	66	26*	40	3
DS - 65,66	44	100	12.7	44	32*	37	3
DS - 67,68	83		16.7	72	53	20	
DS - 69,70	83	30	10.0	90	67	20	
DS - 71	95	75	10.9	95	68	20	
DS - 72 to 75	90		12.1	91	71	20	
DS - 76 to 79	82	50	12.2	91	70	20	
DS - 80	42	80	10.1	39	24*	8	
DS - 81	57	45	11.9	64	44	1	
RVS - 1 to 4	86	74	15.5	84	70	53	8
RVS - 5 to 8	71	50	9.9	72	62	53	8
RVS - 9 to 12	72	30	12.9	72	54	53	8
RVS - 13 to 16	57	37	10.4	66	38	52	8
RVS - 17 to 20	69	64	15.5	72	62	52	8
RVS - 21,22,25 to 27	52	99	12.8	52	33	45	5
RVS - 29,30,33,34	45	65	18.8	48	12*	44	4
RVS - 37 to 39,41 to 44	51	34	11.5	52	33	41	3
RVS - 45 to 52	54	24	11.5	56	32*	41	3
RVS - 53 to 59	66	29	16.7	66	26*	40	3
RVS - 61 to 64, 67,68	44	100	12.7	44	32*	37	3
RVS - 69 to 72	80	60	21.6	90	66	20	
RVS - 75,76	83		16.7	72	53	20	
RVS - 77,80	83	30	10.0	90	67	20	
RVS - 81 to 84	82		13.5	85	60	20	
RVS - 85 to 87	95	75	10.9	95	68	20	
RVS - 89 to 92	84		12.1	95	70	20	
RVS - 93 to 96	80	50	14.8	95	75	20	
RVS - 97 to 99	42	80	10.1	39	24*	8	
RVS - 100 to 102	57	45	11.9	64	44	1	
DSR - 1	94	20	9.2	98	71	20	
DSR - 2 to 3	90	40	11.2	89	66	20	
DSR - 4	94	32	7.9	96	71	20	
DSR - 5	92	35	10.8	98	75	20	
DSR - 6	103		9.4	88	66	20	
DSR - 7	92	30	9.4	96	68	20	

*Froze within 24 hours.

Table 11 (Continued)

Slab Type and Number	Weather of the time of casting			Temperature within 24 hrs. of casting		Number of freeze-thaw cycles	Number of wet freeze-thaw cycles
	Temp. °F	Humidity %	Ave. wind mph	Max. °F	Min. °F		
DSR - 8	94		8.2	95	70	20	
DSR - 9 to 12	95	39	15.1	84	70	20	
DSR - 13	84		23.3	64	56	20	
DSR - 14	58	55	17.4	75	37	20	
DSR - 15	90	39	8.9	88	55	20	
DSR - 16	57	45	11.9	64	44	1	
RVSR - 1 to 3	94	20	9.2	98	71	20	
RVSR - 4 to 5	90	40	11.2	89	66	20	
RVSR - 6 to 8	94	32	7.9	96	71	20	
RVSR - 9 to 11	92	35	10.8	98	75	20	
RVSR - 12 to 15	93	30	11.9	95	74	20	
RVSR - 16 to 18	103		9.4	88	66	20	
RVSR - 19 to 21	92	30	9.4	96	68	20	
RVSR - 22 to 24	94		8.2	95	70	20	
RVSR - 25 to 27	84		23.3	64	56	20	
RVSR - 28 to 30	58	55	17.4	75	37	20	
RVSR - 31 to 33	90	39	8.9	88	55	20	
RVSR - 34 to 36	57	45	11.9	64	44	1	

CHAPTER 4

SUMMARY AND CONCLUSIONS

This project was initiated with the intent of supplementing limited previous work regarding the effects of surface revibration on the physical properties of fresh and hardened concrete. It was anticipated that a practical means might be researched for reducing the amount of cracking which now occurs in slab work, particularly in highway bridge decks. It had been found, prior to this project, that revibration can be performed such that physical properties of the hardened concrete are most beneficially influenced and that deflection cracking prior to initial set can be completely eliminated.

Reported herein are the data collected on 212 slabs cast under a wide variety of ambient weather conditions, and subject to variations in fresh concrete properties, handling, steel placement, top cover on polar, etc. Surface revibration was performed using a quasi-floating vibrator pan---quasi in that the pan was constrained in its possible vertical motion to ± 1 inch. The time at which revibration was performed was altered according to the attained penetration resistance of the freshly placed concrete and varied from 8 PSI to 200 PSI. The guiding criteria for rate of travel of the vibrating pan were strictly dependent on the resulting surface, and the attainment of full reliquification of the concrete under the pan. When this condition was reached, the elimination of pre- and post-revibration cracking was very successful and the surface was generally adequate for final finish except when P.R. was over 100 PSI at which point there was insufficient time to float finish.

It was found that mechanically induced and environmentally caused cracking of all kinds in concrete slabs can be significantly reduced by surface revibration. Taking all slabs into account, 47% of the control slabs showed cracking of some kind one year or more after casting, while only 17% of the surface revibrated slabs showed cracking. All slabs were subject to normal weather conditions at time of casting and thereafter with the project continuing through 3 full years and casting work going on under all conditions except for periods of less than -32°F . In viewing the affects of retarded

concrete when surface revibrated, it was found that 29% of these slabs containing retarder cracked while only 12% of those with non-retarded concrete showed any cracking. One must, therefore, be alert to the greater possibility of cracking if chemical retarders are used, even though revibration is also used. However, even here a 56% improvement can be realized, even though less attractive than the 240% reduction with non-retarded concrete.

Another significant finding was that surface revibration seemed to eliminate the effects of cover on top reinforcing, with the same percentage cracking found in very thin cover as was found in cover between 1 1/4 to 1 3/4 inches. The economic implications of this finding are obvious when one considers that recently the minimum design cover has increased resulting in cost increases of significant properties.

Although not a part of this study, it was found that linseed oil curing is most effective in reducing environmentally caused cracking, so much so that its use was curtailed on this project due to its masking of the effects of revibration.

As a compliment to the project, separate studies were conducted in an attempt to define why the physical properties were improved by revibration. Increases in the amount of hydration products were found as partial contributors, along with consolidation improvements. The improvement in w/c, although not measured because of the difficulty of determining this in hardened concrete, was, nevertheless, obvious as one noted the change in moisture content due to water losses from bleeding, evaporation, absorption into forms, and aggregate water separation at the joints of forms, and hydration of cement grains. All these contribute evidently to the improvement in final physical properties when reliquification takes place with vibration prior to initial set.

For practical purposes, surfacing revibration should be done prior to attainment of a P.R. of 60 PSI. A surface ready for finish is produced by the floating pan and yet sufficient time has lapsed to attain many of the other desirable changes in the concrete.

One factor has been found which may cause concern, namely the erratic air void spacing in the top 1/4 inch of concrete. In some instances (not all) there was found a spacing greater than 0.001 inch.

In conclusion, surface revibration is a practical means for reducing the cracking which occurs in bridge deck slabs. It eliminates or reduces many contributing factors which have often made cracking impossible, difficult, or annoying to control.

APPENDIX A

A STUDY TO DETERMINE CHANGES IN RATE OF HYDRATION AND MORPHOLOGY IN TYPE I PORTLAND CEMENT PASTE CAUSED BY REVIBRATION

APPENDIX A

A STUDY TO DETERMINE CHANGES IN RATE OF HYDRATION AND MORPHOLOGY IN TYPE I PORTLAND CEMENT PASTE CAUSED BY REVIBRATION

Revibration of concrete will increase the strength after any period of delay as long as the mix can be brought to a plastic state (1,2,3,4 and 5). The maximum increase in strength appears to occur when revibration takes place between 200 and 400 (initial set) PSI penetration resistance. Not only is the strength of concrete improved, but also the density and modulus of elasticity are increased. (5)

The revibration referred to in the literature is principally performed internally or on vibrating tables. Hilsdorf and Lott (6) provide the only instance where revibration is noted to have caused no change in strength and to have had a possible negative influence on durability. However, their study stands alone in that it was performed as surface revibration of slabs of retarded concrete and, therefore, brings in an additional parameter or two not considered in the other papers.

There have been several reasons suggested to explain the increase in strength and other properties. These can be summarized as follows:

The concrete is more densely consolidated, filling the voids left after initial placement and those resulting from absorption and evaporation of water, thereby permitting more advantageous development of the hydration products

It has also been proposed that the laboratory disturbances (vibration) in some way affect the extent of, or the production of, hydration products. Sawyer and Lee comment that:

" The initial structure is determined by either the C_3A or C_3S , whichever hydrate comes first. In a normally retarded set, the C_3S is presumed to hydrate first and to establish the primary or principal structural bonds. If, on the other hand, the C_3A hydrates first, revibration may displace the first structure and allow the normal structure of the C_3S to develop, as

in an otherwise normally retarded set. The extent of hydration of C_3S is relatively insignificant up to four to six hours, while that of the C_3A may be (unless normally retarded) almost complete within ten hours. These factors could have significant influence on the rate of strength of development as well, and even on ultimate strength." (5)

The present study was undertaken in an effort to observe possible changes in strength due to hydration and morphology changes of Type I Portland Cement paste when subject to revibration. The rate of reaction for the major compounds of Type I cement, i.e., C_3S and Beta C_2S and C_3A , were determined from X-ray defraction. Microstructural changes of the cement gel were observed under a scanning electron microscope on fracture surfaces of cement paste samples.

Background Information

Constituents of anhydrous cement. Anhydrous Portland Cement consists of four major compounds, namely:

tricalcium silicate, $3CaO \cdot SiO_2$... abbreviated C_3S

dicalcium silicate, $2CaO \cdot SiO_2$... abbreviated C_2S

tricalcium aluminate, $3CaO \cdot Al_2O_3$... abbreviated C_3A

tetracalcium aluminoferrite, $4CaO \cdot Al_2O_3 \cdot Fe_2O_3$... abbreviated C_4AF

Other minor compounds, such as free lime, oxides of alkali, etc., are present in small amounts composing typically less than 5 percent of the total, and their hydration products contribute little to the cementing action of the hydrated cement paste. The major constituent of Portland Cement, that is C_3S , is sometimes referred to as alite. It does not occur in a pure form in ordinary cements. Oxides of aluminum and manganese are typically present in small amounts, and their presence may have an influence on its strength-producing properties. (6)

The second silicate of calcium which exists in ordinary Portland Cement and which next to C_3S makes up the largest percentage of the total volume is Beta dicalcium silicate. This polymorph of C_2S can incorporate many other substances as it moves into its solid solution, such as oxides of alumina, magnesia, and alkali which occur in the solid solution.

C_2S has a lower C/S molar ratio than does C_3S , and the molecular structure is somewhat more dense than in C_3S . This may in part contribute the difference in the rate of hydration between the two with dicalcium silicate reacting slower than the tricalcium silicate.

Tricalcium aluminate exists in a relatively pure form in Portland Cement. It composes about 10 percent of Type I Portland Cement. A ferite phase of tricalcium aluminate also exists, commonly referred to as tetracalcium aluminiferite, although the ratio of A/F is not fixed. The other minor constituents such as free lime, alkali oxides, oxides of magnesia, phosphate, and SO_3 exist in the cement clinker.

Hydration of Cement

The hydration of cement compounds starts as soon as it comes in contact with a sufficient amount of water so that a relative vapor pressure in excess of 0.8 can be maintained. It is generally assumed that the hydration rate and the hydration products which occur in Portland cement paste are essentially the same as are observed for the pure compounds. The hydration of the calcium silicates is very important in the overall hydration process of Portland cement. These compounds typically make up about 75 percent of the total mass of cement, and their physical properties in the pure form are almost identical to those of concrete made with Portland cement.

Both of the calcium silicates, C_3S and Beta C_2S , produce hydrates of essentially the same morphology, but their Ca/Si molar ratio surface development and rate of hydration does vary. The rate of hydration can be observed in Figure A-1. It should also be noted that C_3S has a greater C/S ratio than Beta C_2S and produces about three times as much calcium hydroxide as does the latter. C_3S reacts very rapidly when placed in contact with water, and during the first five minutes, the rate of hydration is exceedingly high. As the coating of unstable calcium silicate hydrate develops around the grain, the diffusion of water molecules through the coating begins to control the rate of reaction. A disturbance of this coating, whether by self-dessication or by mechanical abrading, will therefore have an influence on continued hydration of the inner cement particle.

The rate of hydration of the products of C_3A depends to a large extent upon the amount of gypsum present. It is a common practice in these days to add gypsum to the raw cement at the point of manufacture in order to control early false set initiated principally by the aluminate compounds. However, the presence of gypsum appears to have little effect on the rates of hydration or the reaction products of the two calcium silicate compounds but does affect C_3A and C_4F considerably.

From Figure A-1 it may be noted that the rate of reaction of tricalcium aluminate is very rapid, although as noted in Figure A-2, its overall contribution to strength is minimal. Apparently, the physical properties which are observed during the early stages of hydration of Type 1 Portland Cement concretes are those imparted by C_3S . However, after about one year, the hydrates of Beta C_2S have reached a point of producing almost identical physical properties as those observed in the C_3S .

The Physical Nature of Hardened Cement Paste

The actual mechanism of hydration and the formation of cement gel is still not completely understood. Specific volume data indicates that the process of hydration results in an increase in the bulk of volume of solid material, 1 cc of anhydrous cement producing about 2.2 cc of cement gel. Although there is a doubling of the solid volume during hydration, the overall volume of cement paste increases by only minute amounts on the order of 0.6 percent. It must be concluded, therefore, that hydration occurs in the following manner: immediately after mixing, the unhydrated cement particles in a fresh paste with a water/cement ratio of about 0.5 are dispersed in an aqueous solution and a cement gel forms a coating around the grains. As hydration proceeds, some hydration products and crystals of calcium hydroxide are precipitated from the saturated solution in the capillary pores or spaces. About 45 percent of the gel forms inside the original boundary of the cement grain and 55 percent is deposited on the surrounding capillary spaces. Thus, the cement gel forms around, grows out from, and replaces some of the original cement. Once bridging has occurred between particles, the past stiffens into its final shape, 4 to 6 hours after mixing. Further hydration involves a complex form of diffusion in which water

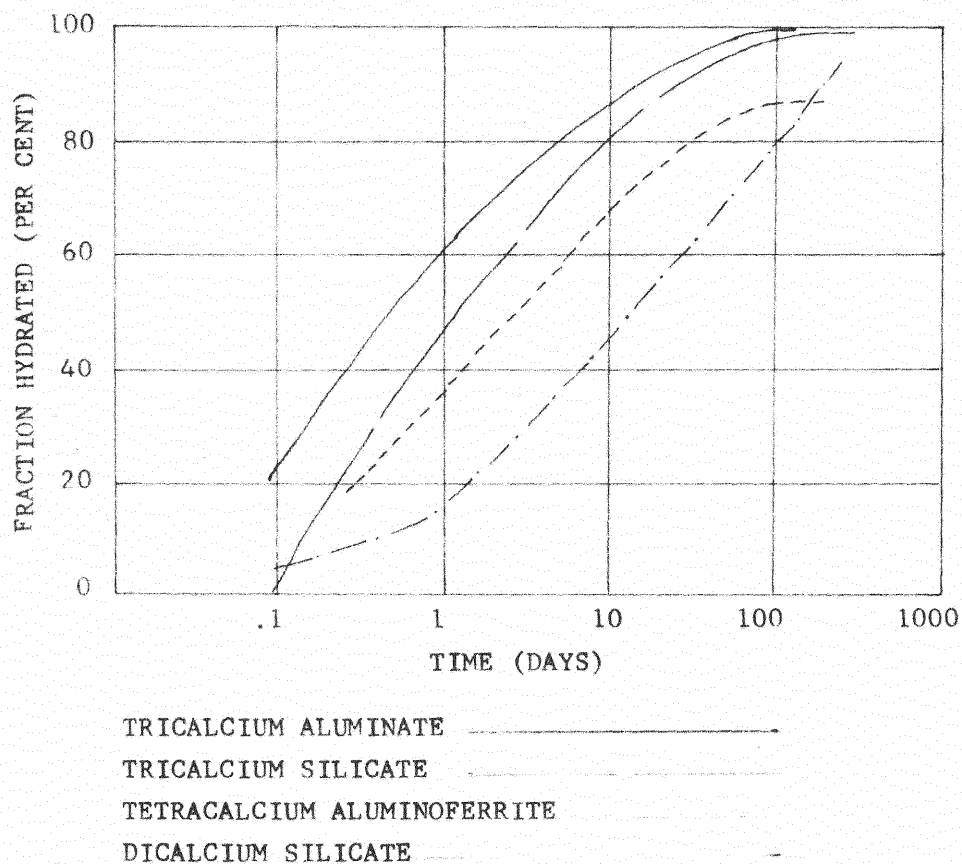


Figure A-1 Speed of Hydration of the Four Major Compounds in Portland Cement. (2,15)

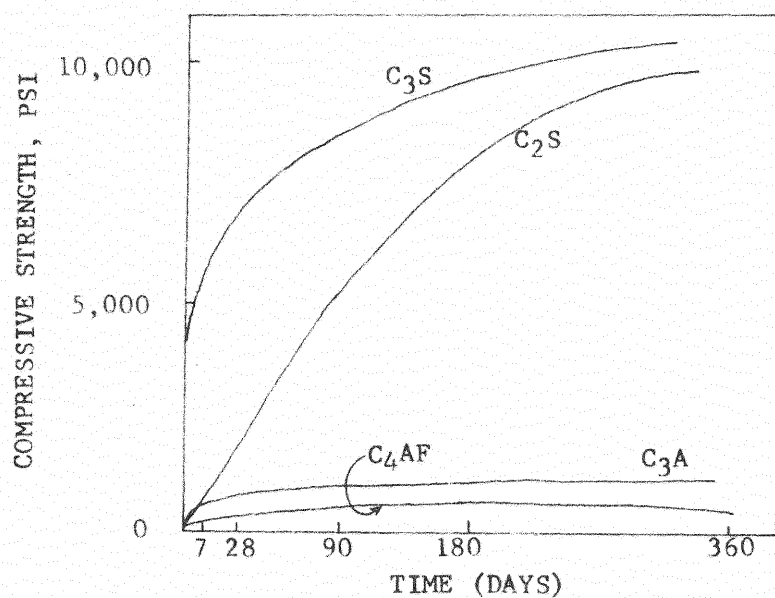


Figure A-2 Graph of Typical Strength Development by Portland Cement Compounds, (2,13,15)
A-5

from the capillary spaces diffuses inward to the gel pores while the calcium silicate components move in the other direction. Since more cement gel is not deposited in existing gel pores, these must be too small to allow the nucleation of a new solid phase. In the latter stages, hydration continues at a very slow rate and even under ideal conditions may not be completed for over 25 years or more.

At the early stages of hydration, free or uncombined water is present in the form of large continuous capillary pores or channels. Hydration involves deposition of the cement gel in the capillary space and a stage may be reached when sufficient gel is formed to block the originally continuous capillary channels. Any capillary water remaining is present in isolated capillary channels. Once these cavities are filled, hydration will cease because there is no further room for new gel formation. Since 1 cc of cement produces 2.2 cc of gel, there must be at least 1.2 cc of water filled spaces initially if complete hydration of the cement is to occur. This corresponds to an initial w/c ratio of 0.38 by weight. Only those cement pastes with w/c ratios greater than 0.38 have sufficient water filled space for all the unhydrated cement particles to be converted into gel. The formation of gel also depends on the presence of water in the capillary channels or cavities. The larger capillary pores become empty at relative water vapor pressure of less than 0.8 and if the cement paste dries out below this level, hydration virtually ceases.

Morphology of Hardened Paste

The hydration products of calcium silicate show different morphologies depending upon the Ca/Si ratio at room temperature. The products are crystalline, ill-crystalline, and amorphous in nature. Microscopic observations of calcium-silicate-hydrates show that all three types of morphologies are simultaneously present, and it becomes a major problem to isolate the factors responsible for a given structure. Continued access to water and the freedom to discard Ca^{++} ions in the surrounding water are factors which affect the hydration of calcium silicates.

Electron micrographs show that the CSH (I) hydrates consist of extremely thin crumpled sheets or crinkled foils only one or two molecular units thick. As the CaO/SiO_2 ratio increases the particles gradually change until, at lime saturation, CSH (II) hydrates are composed of fine, fibrous, or needle-like crystals up to about one micron in length and $500 \text{ \AA}$ wide. As the lime solution concentration increases, the crumpled sheets twist and roll up into long tubes or fibers. In a similar manner the particle nature of tobermorite gel from the C_3S and C_2S pastes depends on the lime concentration. The low lime tobermorite consists of large (one micron) flocks of foil-like material, whereas in lime saturation some of the foils have rolled up into thick fibers. In supersaturated solutions, large dense flocks are formed but at the edges of these flocks a felt-like texture of interlocking fibrous particles is observed, a structure which has also been noted when the amorphous flocks are broken up.

When tricalcium silicates first come into contact with water, small platelets form at the surface of the grains. These are C-S-H with very high Ca/Si ratios and may be responsible for the high surface area found for these hydrates. These products have high Ca/Si ratio and contribute to Ca^{++} ions being discharged into the surrounding water. Copeland and Schulz observed that these platelets disappear after one hour. At about the time of initial set, a growth of acicular particles was seen at the surfaces. Copeland further observed that these lathlike particles stop growing lengthwise and join up sideways.

The growth of hydration product, however, is not only outwards, but inward into the grain. The amount of inner hydrated products, sometimes referred to as pseudomorphs, is estimated to be 45 percent of total hydration products. Very little is known so far about the pseudomorphs.

The outward growth of calcium silicates is mostly needle-like. These needles grow radially outward. Sometimes a reticular structure is observed on the surface grains. These cells seem to form by the joining of the fine fibers that grow sideward from the main needles. As the hydration proceeds, these particles grow and join with the growth from other particles. The joined portion may or may not have a different

morphology. Ciach, et al., (7) noted that the fine fibers bridge the gap between the acicular tubular products and create an interlocking mesh. The space between the fibers fills, if at all, with amorphous material. The final product consists of plates made up of fine fibers and amorphous material with marked cleavage. The formulation of plates seems to be inconsistent with the radial growth of needle-like particles.

Williamson (8), in his detailed study of C-S-H, observed a prominence of fibrous growth radiating outward with rounded tips. Sometimes the growth may look like tendrils.

The calcium hydroxide (CH) phases first appear as spherulites or rounded platelets. The CH particles grow into well developed crystals, mostly in the form of hexagonal prisms; frequently they show internal striations indicating the presence of inter-lamellar inclusions.

Apparently the large CH crystals do not form very rapidly. As the concentration of Ca^{++} and OH^- ions increase, the water becomes supersaturated with them. The CH crystals slowly precipitate out into the water-filled spaces, but grow rather rapidly. Sometimes the growth is so rapid that it may surround the grains of calcium-silicates. (8) The growth and amount of calcium hydroxide in cement paste may or may not have an effect on the strength of cement paste and the fracture plane. It is still an unsolved issue.

Relationship Between Microstructure and Strength of Portland Cement

Among the many factors which affect the strength of cement paste, Powers (9) shows that the main factors contributing to the strength of cement paste are porosity and a gel/space ratio. The strength seems to be approximately proportional to the cube of the gel/space ratio. Numerical values change little for different chemical compositions of cement. This concept has, of course, emphasized the importance of the development of the gel and its structure.

Calcium silicate hydrates have very high strength compared to the other components of cement. However, it is not yet known how much semicrystalline and amorphous material help in producing strength. Calcium aluminate hydrates contribute very little to strength. Ettringite formed at early stages helps in bridging voids, but if produced in later stages of hydration causes some disruptive pressures. (10)

Calcium hydroxide which is precipitated in originally water filled spaces does not appear to exert disruptive forces. (10) However, its growth is quite rapid and sometimes forms into chains. The crystal has lamellar structure and hence is easily fractured along the cleavage planes. The presence of calcium hydroxide may or may not have weakening effects on the eventual strength.

All indications are that the primary source of strength found in hydrated cement occurs as a result of the outer products of hydration of the calcium silicate. The amount of bridging which takes place between grains and the morphology of the material that is formed between those grains. It is highly probable that the observed increases in concrete strength due to revibration of the concrete may, in fact, result from a closer particle proximity together with a disturbance of the initial gel structure and an opening of additional capillary avenues for continued hydration at a different rate than that which would proceed under normal conditions without revibration.

Specimens and Procedures. This experimental investigation was carried out in two stages, both using common specimens of revibrated Type 1 cement paste, the properties of which are shown in Table A-1, namely, Series 1, X-ray diffraction studies and Series 2, scanning electron microscope studies. Cement paste cylindrical specimens of 1/4 inch by 1 inch were prepared using Type 1 Portland Cement with a water cement ratio of 0.5. The cylinders were prepared by pouring the previously mixed cement paste into the cylinder in three layers, stirring and rodding each layer with a small wire (0.03 inch diameter) to drive out air pockets and to permit a degree of consolidation. All except control samples were then revibrated at approximately 2 hours and 45 minutes after the mixing of the paste as shown in Table A-2. Revibration

PORTLAND CEMENT PROPERTIES**NORMAL CONSISTANCY****24.8 %****FINENESS (BLAIN)****3680 cm²/g.****INITIAL SET****3 Hrs. 20 min.****FINAL SET****5 Hrs. 15 min.****COMPRESSIVE STRENGTH (3 Days)****2990 psi.****(7 Days)****4450 psi.**

Table A 2

REVIBRATION PARAMETERS

Specimen Designation	X-1	X-2	X-3	X-4	X-5
Time After Mixing Till Revibration min.	152	162	174	175	170
Period of Revibration min.	1.5	1.5	1.5	1.5	1.5
Vibrator Frequency hz.	100	130	160	100	100
Vibrator Amplitude $\times 10^{-3}$ in.	14.68	8.68	5.74	7.84	14.68
Vibrator Acceleration g.	15	15	15	8	15

was performed on three separate sets of specimens. With each set the frequency and amplitude were changed while maintaining a constant acceleration g . Values of frequency, amplitude, and acceleration selected are those common to vibrators used in the concrete industry.

Revibration of the specimens was performed on a vibrating table (permanent magnet shaker model) with controls for accurately maintaining the vibration parameters. After revibration, specimens were kept in moist curing for the first 24 hours and thereafter immersed in water except as noted in the following.

Those specimens to be tested by x-ray defraction were removed from curing according to the following schedule: 4 specimens at 4 hours, 4 specimens at 8 hours, 4 specimens at 24 hours, and 4 specimens at 7 days. Immediately after removal from curing, x-ray defraction specimens were prepared by grinding the cylinders to a fine powder and passing through a No. 200 seive. Hence, put in a uniform thin layer on a waxed glass slide and placed in the x-ray defraction machine. With the glass slide placed in the x-ray defraction machine, a pattern was obtained at a standard rate of $20 = 1$ degree per minute with a resulting standard x-ray defraction chart obtained.

Specimens to be viewed in the electron microscope were removed from curing after 7 days and placed in an oven to dry at 110°C for 2 days. The cylinders were then fractured, and the fractured surface coated with a gold palladium vapor under a vacuum of 4×10^{-5} millimeters of mercury. The specimens were constantly rotated during the evaporation process to obtain a uniform coating of approximately 100 to 200 Å thick. The specimens were then replaced in the oven and kept at 110°C until viewed in the electron microscope.

Test Results

X-Ray Defraction Study. From the x-ray defraction chart, peaks of the major cement compounds were identified, and the approximate percentage of C_3S , Beta C_2S , and

C_3A were calculated by the area under their respective peaks (see Figure A-3), and the cumulative percentage hydrated of each compound computed by taking the ratio of the respective areas to the areas found from a test taken at 120 days (assuming at 120 days essentially complete hydration). Results of the x-ray defraction test are given in Table A-3 where it is apparent that a greater degree of hydration has taken place in all of the revibrated specimens at any particular time as compared to the control specimen. However, the difference in the percentage of hydration product at early ages is greater than at later stages indicating that the influence of revibration on the percentage of hydration product decreases with time, and that eventually one might expect the same amount of hydration at later stages in both control and revibrated specimens.

The differences in the amount of hydration of a given compound for different levels of vibration parameters are only slight. Although tendencies appear to exist, additional replications will be required in order to statistically substantiate any inference here. In comparing the control specimen of each compound with the average of the revibrated specimens, a statistically significant difference exists ($\text{Alpha} = 5$ percent) in all cases. Figure A-4 is a plot of the control specimens together with the average of the revibrated specimens and clearly shows the general tendencies. The influence of revibration is most noticeable in the early stages of C_2S where a 250 percent increase in amount hydrated is obtained partially due to the very slow hydration in the early stages of C_2S . Also noticeable is the 33 percent increase in percentage of hydration product between the control and revibrated specimens of C_3A at the early stages; however, this declines to a 9 percent increase or difference at 7 days. Figures A-5 through A-7 further show the influence of revibration.

Electron Microscopy Study. The fracture surfaces of eight different specimens were observed in the electron microscope after seven days of water curing, thence, drying at 110°C . Two specimens each were observed from the control series, series X-1, series X-2, and series X-3. Figures A-8 through A-16 are micrographs typical of those taken in this series of tests. Views of the control specimens are given in Figures A-8 through A-11, of specimen X-1 in Figure A-12, of specimen X-2 in Figures A-13, 14 and X-3 in Figures A-15, 16.

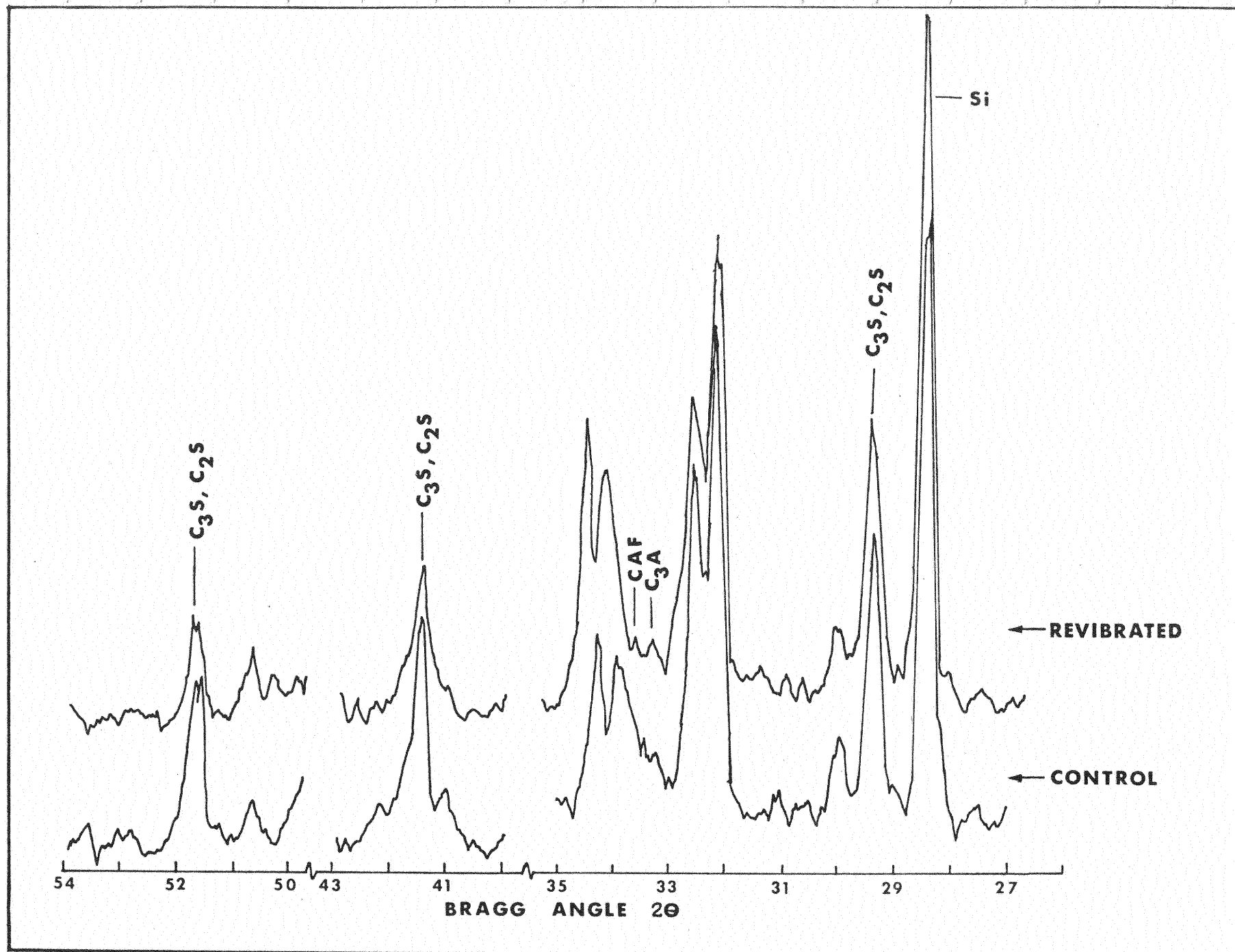


Figure A-3

Table A-3

The Percentage Hydrated of C_3S , C_2S , and C_3A as a Function of Time
for Control and Samples Revibrated at 2 hrs. 45 min. After Mixing

Time		4 hr.	8 hr.	24 hr.	7 days
Compounds	Sample No.				
C_3S	C	6.98	10.21	16.18	61.68
	1	9.26	16.70	19.12	64.92
	2	8.75	13.00	18.56	64.27
	3	8.17	13.28	18.05	64.54
	Average of 1,2 & 3	8.72	14.32	18.57	64.57
C_2S	C	0.99	2.13	4.71	44.02
	1	2.96	4.07	7.84	48.97
	2	2.01	3.48	6.71	47.00
	3	2.44	3.19	7.57	48.3
	Average of 1,2 & 3	2.47	3.58	7.37	48.09
C_3A	C	24.91	50.17	58.00	75.18
	1	34.53	52.34	60.20	77.82
	2	33.71	52.03	60.66	81.05
	3	30.05	54.40	61.00	85.67
	Average of 1,2 & 3	32.76	52.92	61.28	81.51

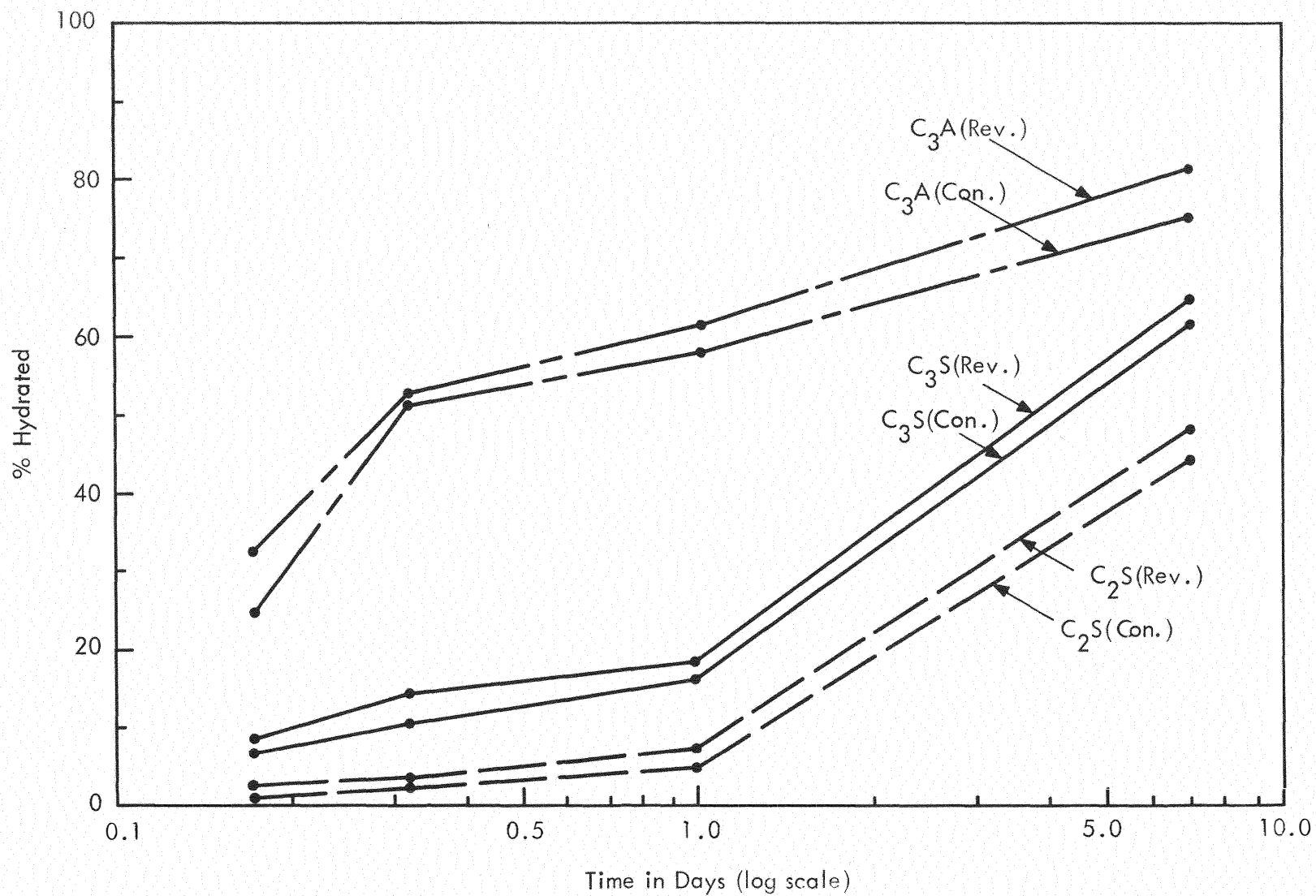


Figure A-4. Hydration of Type I p.c. Cement Compounds With Time As Determined By X-Ray Diffraction for United and Revibrated Specifications.

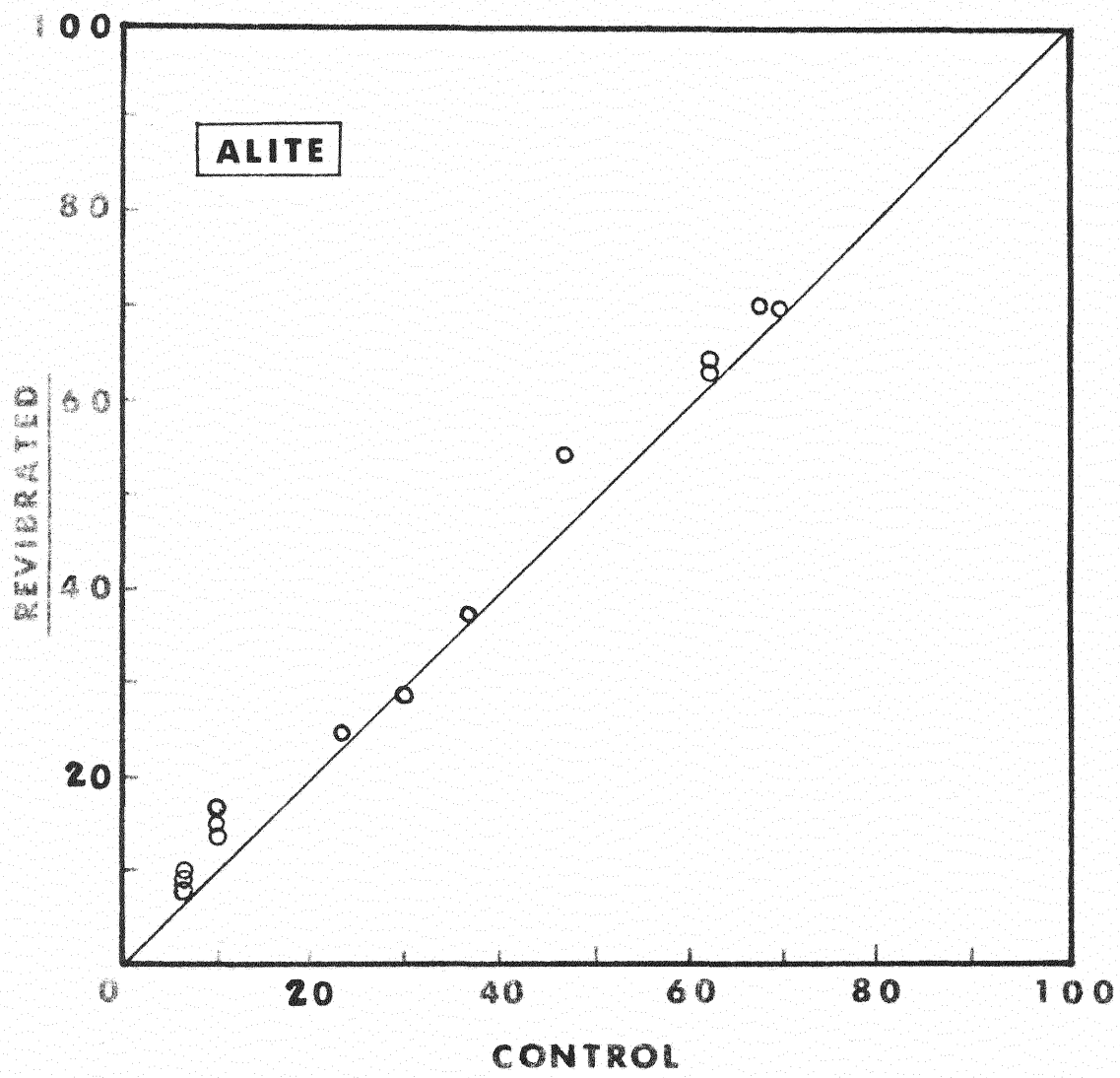


Figure A-5.

Percent Hydration of C_3S for Companion Pastes
At Varying Ages Under Control and Revibrated Conditions.

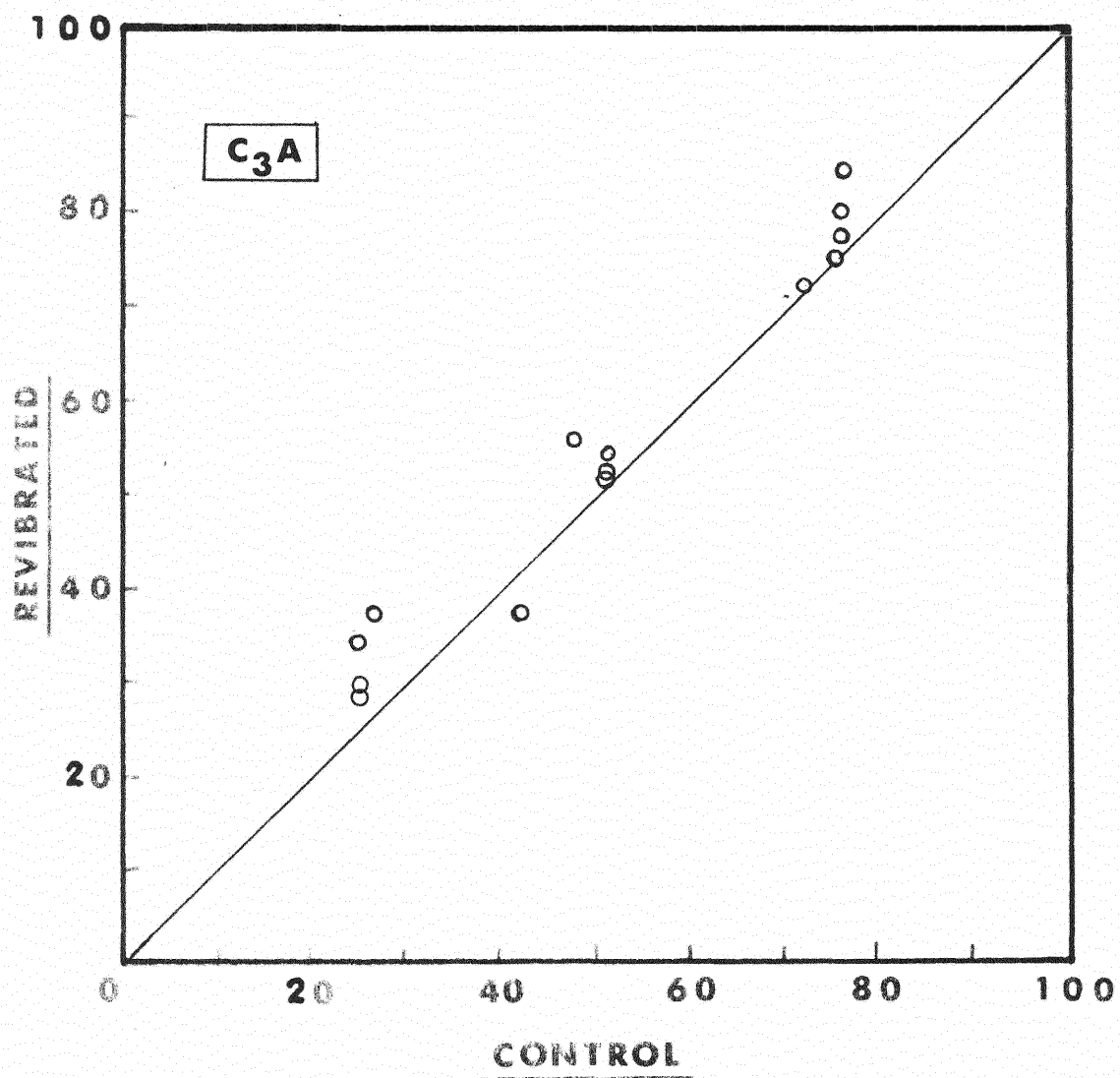


Figure A-6.
Percent Hydration of C_3A for Companion Pastes at
Varying Ages Under Control and Revibrated Conditions.

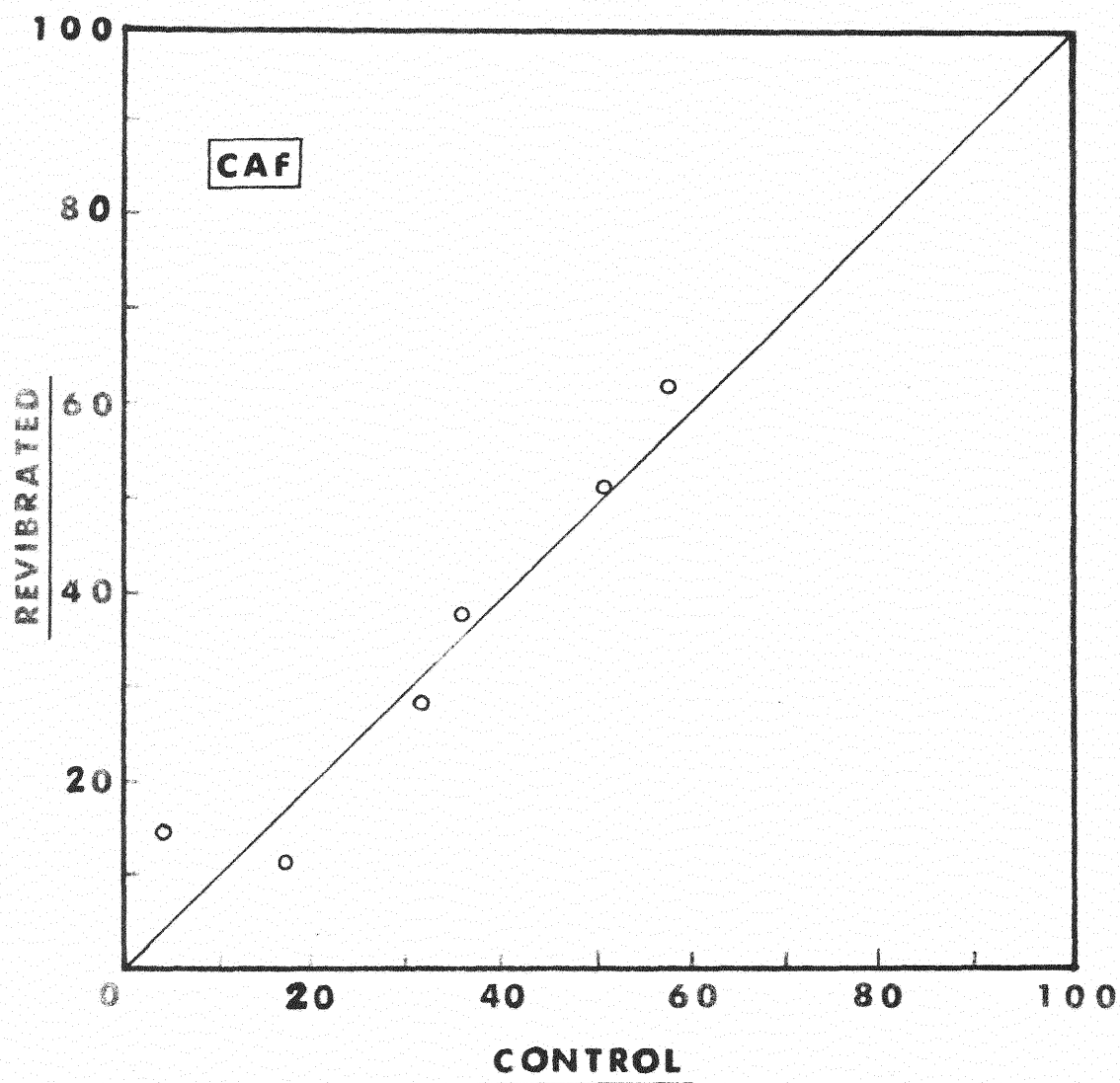


Figure A-7.
Percent Hydration of CAF for Companion Pastes at
Varying Ages Under Control and Revibrated Conditions.

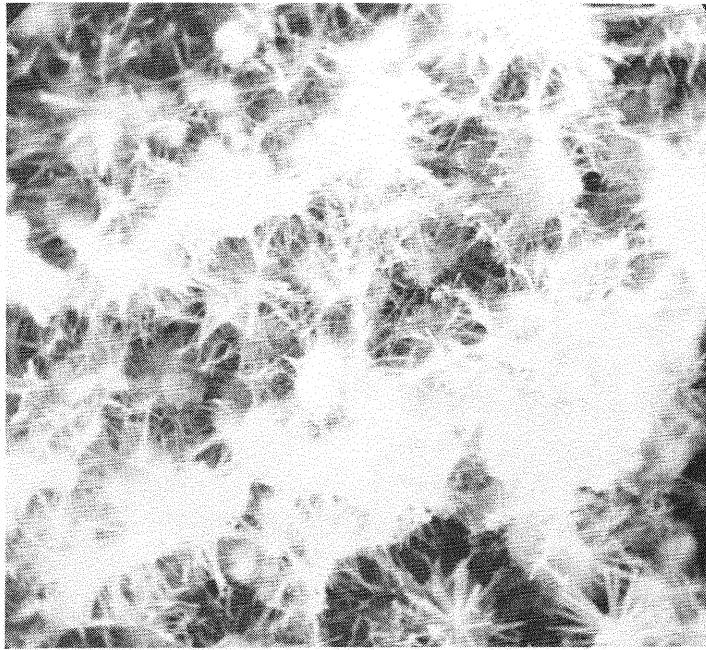


Figure A-8. Electron Microscope Photograph of a Fracture Surface of Ordinary Cement Paste, Hydrated for 7 Days (Control).

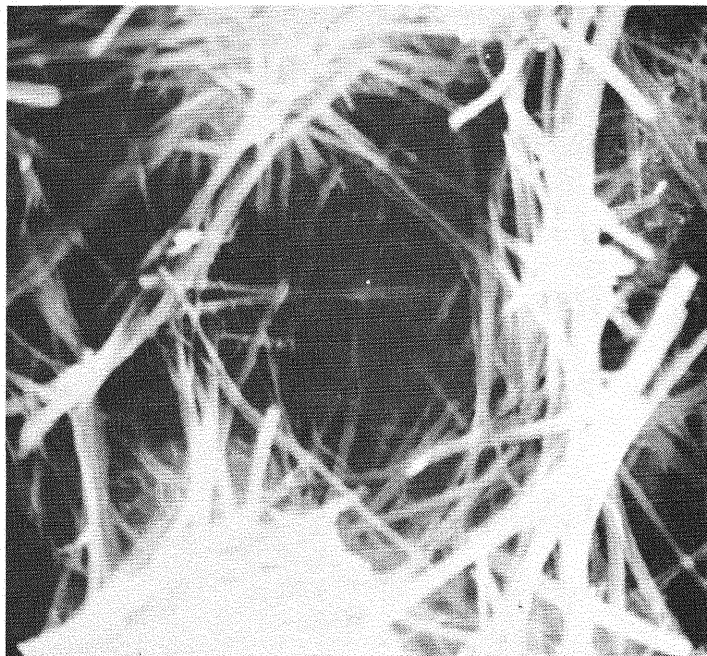
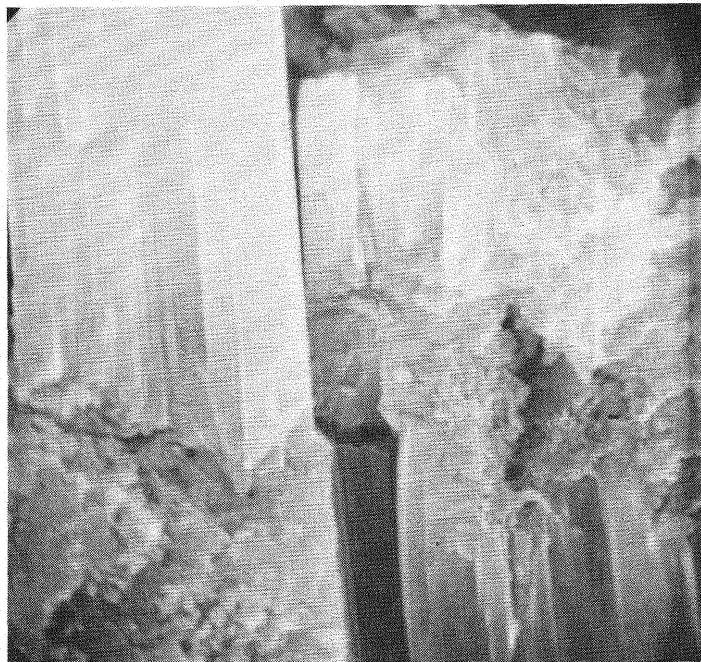
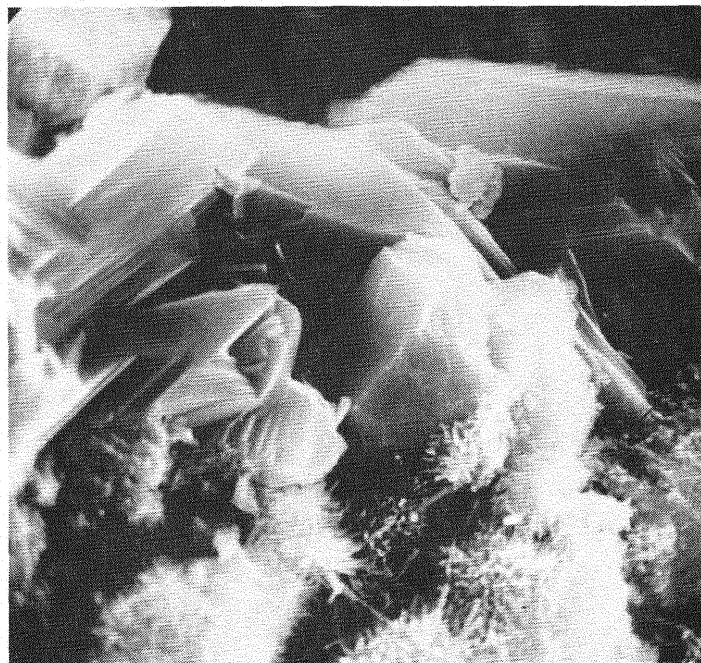


Figure A-9. Intergrowth of Tubular C-S-H in Ordinary Cement Paste (Control).



(a)



(b)

Figure A-10. Crystal Growth of Calcium Hydroxide in Control Specimen and Complex Fracture of CH in X-2.

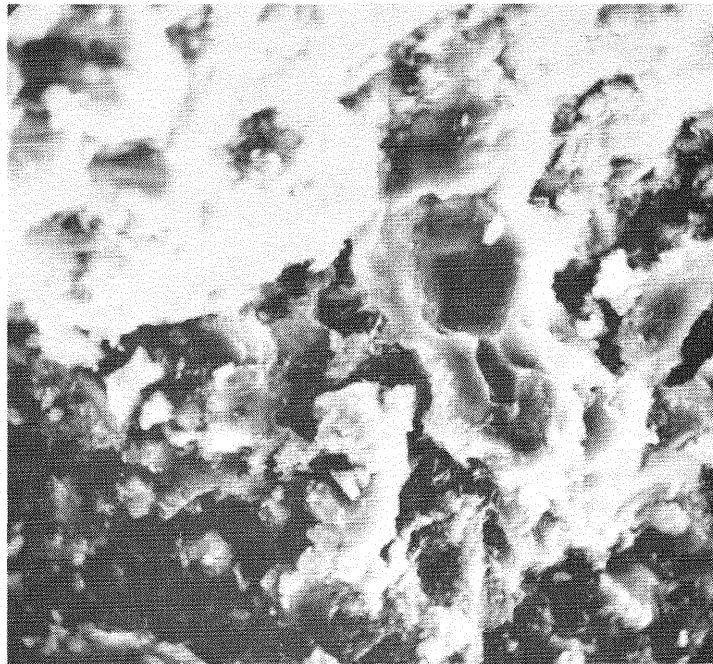


Figure A-11. Electron Microscope Photograph of a Fracture Surface of Ordinary Cement Paste, Hydrated for 7 Days (Control).

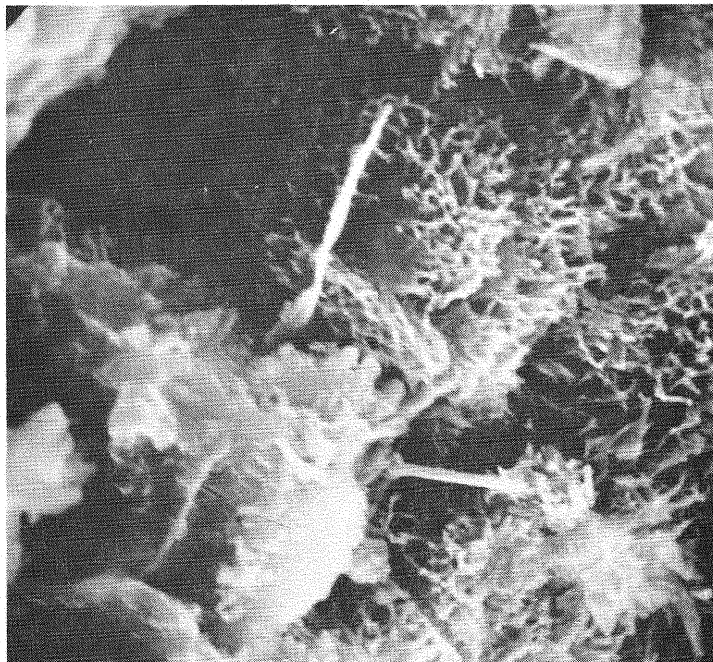


Figure A-12. Fibrous Growth of C-S-H in Revibrated Specimen (X-1).



Figure A-13. General View of Fracture Surface of Revibrated Specimen (X-2).



Figure A-14. Calcium Silicate Hydrate in Revibrated Specimen (X-2).



Figure A-15. Fracture Surface of Revibrated Cement Paste After 7 Days of Hydration (X-3).

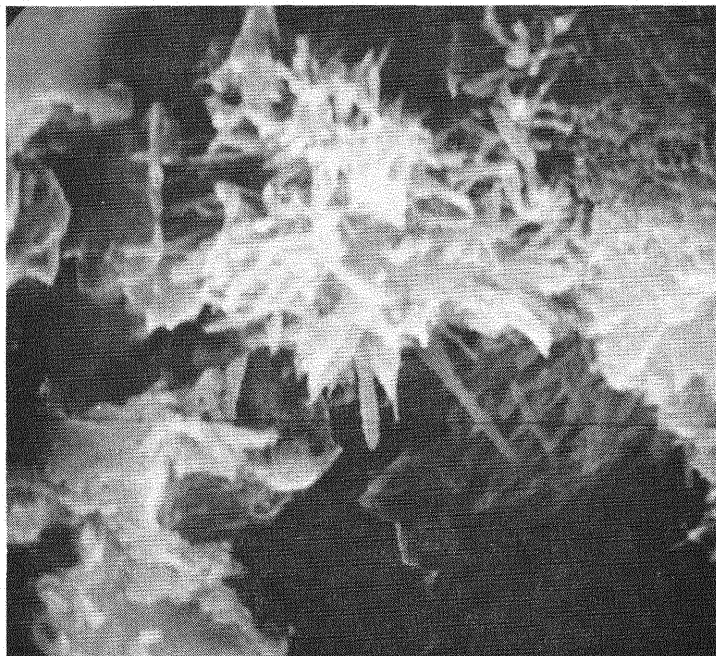


Figure A-16. View of Growth of C-S-H After 7 Days of Hydration of Revibrated Specimen (X-3).

A porous mass of calcium silicate hydrate is shown clearly in Figure A-8 with a spot enlargement shown in Figure A-9. The tubular structure is the predominant feature with the needle-like fibers growing radially outward from the cement grains. Bridging of these needles is seen in many places, and in the left central portion of the picture, a growth of fine fibers is seen in between the larger fibers. A relatively high percentage of calcium hydroxide crystals was found in the control specimens. These crystals are shown in Figure A-10. Note that Figure A-10b shows an interesting chain-work of CH crystals with a complex fracture. Some of the crystals have fractured along their cleavage planes while the more complex fracture is seen to be against the plane. Another often occurring crystalline structure is the amorphous structure found in Figures A-11, A-13, and A-15. The calcium silicate hydrate shown in Figure A-14 is very typical of that found in a compact mass. Note that there is a growth of long needles as well as short fibers. The long needle-like structure bridges between the grains with the shorter fibers growing between the needles and providing strength to the grains themselves. This same general tendency for CSH crystal and needle-like crystals to form an abundance was noted in specimen X-3 shown in Figure A-16. The reticular network shown on the surface of a grain in Figure A-12 shows very little growth of the thick columnar structural type. Williamson (8) attributes this type of structure to poor hydration.

In summary, no conclusions can be drawn from the electron microscope study. In looking at many of the micrographs of control specimens versus revibrated specimens, it appears that the structure is somewhat more compact in the revibrated specimen pictures. However, this would require an extensive series to substantiate. There also appears to be a greater percentage of needle-like structures in the revibrated specimens indicating more extensive CSH. Finally, the occurrence of CH crystals was apparently less frequent in the revibrated specimens. It should be emphasized that in each of the above notes, the extent of sampling, the number of micrographs, and the percentage of area photographs for each fractured specimen are each insufficient to draw any firm conclusions and are at this point good for inferences only.

Conclusions

1. There is a statistically significant increase in the rate of hydration products of revibrated samples of cement paste when compared to control samples. This conclusion is based solely on a series of tests using Type I Portland Cement paste at a 0.5 water cement ratio revibrated about 2 hours and 45 minutes after mixing. However, it was found to be true for the compounds C_3S , Beta C_2S , and C_3A .
2. The general shape of the hydration curve of each of the compounds C_3S , Beta C_2S , and C_3A was not affected by revibration; merely offset in an upward direction.
3. Early age effects on percentage of hydration of cement compounds is more pronounced than at later ages, eventually diminishing to an insignificant difference of revibrated specimens over control specimens.
4. The morphology of fractured cement paste specimens shows an apparently slight increase in the amount of C-S-H crystals in the revibrated specimens over that found in the control specimens.
5. Calcium hydroxide crystals appear to be more predominant and well formed in the control specimens versus the revibrated specimens.

Implications of this study are obvious: that one might well expect additional strength and improved other physical properties in concrete subject to revibration at a stage prior to initial set. The exact timing and permissible limits are yet to be established, but the method holds obvious promise.

APPENDIX A

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APPENDIX B

A STUDY TO DETERMINE THE INFLUENCE OF SURFACE REVIBRATION CONCRETE SLABS ON THE PHYSICAL PROPERTIES OF THE HARDENED CONCRETE

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CONCRETE SLABS ON THE PHYSICAL PROPERTIES OF
THE HARDENED CONCRETE

INTRODUCTION

In their report on the effects of surface revibration on laboratory concrete slabs, Hilsdorf and Lott (1) concluded that revibration had no statistically significant effect on the compressive strength of retarded concrete, and only a minor favorable effect on non-retarded concrete. There were similarly no pronounced effects on unit weight, abrasion resistance, nor on air void systems except at the very surface of the slab. However, the data on which the strength conclusions were based were not only limited in number but utilized specimens which were not "surface" revibrated, as were the slabs in their investigation. Rather, the compressive tests were obtained on 6x6x18 inch concrete prisms which were revibrated by placing them on a shaker table and vibrating them, at the same time placing a metal plate on the surface of the prisms in hopes that this might simulate a vibrating pan. Obviously, revibration performed on the shaker table was significantly different than that which might be obtained under regular field conditions where revibration was performed on the surface only of stationary slabs. Therefore, it is concluded that the effects on strength of surface revibrated slabs have been only eluded to in their study.

The purpose of the research program here reported was to obtain data on the observable changes in compressive and tensile strengths of concrete slabs along with unit weight and air void distribution in the concrete when subjected to surface revibration. Determination of these parameters was made by coring cylinders from the slabs performing standard as the tests thereon. Included in the study were vibrator frequencies ranging from 47 hz. to 175 hz., acceleration ranging from 2.3 g. to 18.5 g. and penetration resistance of the concrete at the time of revibration from 20 PSI to 500 PSI.

TEST PROGRAM

A total of thirty plain concrete slabs were cast with a water-cement ratio of 0.43 and a medium consistency. Mixed proportions are shown in Table B-1. Type 1 cement was used with an air-entraining admixture to produce between 4 and 5 percent air. Fresh concrete properties together with weather conditions at the time of casting are given in Table B-2 for each of the slabs. The test slabs were cast in wooden forms, 30x18x7-1/2 inches deep, and the forms were coated with a layer of linseed oil prior to casting to inhibit water absorption and to provide bond break. The concrete was placed in the forms and spud vibrated into place. A total internal vibration time of approximately 25 seconds was allowed per slab with the spud inserted at five different locations for about 5 seconds each. After placement and internal vibration, the surface was screeded and lightly float finished. A portion of the concrete used for each slab was screened through a No. 4 sieve and placed in a 6-inch diameter container to a depth of approximately 6 inches, which was then used for penetration resistance measurements.

Three vibrators were used for surface revibration. Their designation and properties are shown in Table B-3. The number one vibrator was equipped with a frequency control system which was varied at three set levels. The vibrators were bolted to a double channel steel section which in turn was welded to a 1/8 inch steel plate forming the vibrating pan 17 inches long by 18 inches wide.

When the concrete in the slab form had reached the predetermined penetration resistance, the surface was vibrated using the floating pan moving at a travel speed of about 2-1/2 feet per minute. Visual observation of the surface before and after revibration were noted, and the surface was then trowel finished and a linseed oil curing compound sprayed thereon at about 175 square feet per gallon. Control specimens were given the same treatment except not revibrated.

Three weeks after casting, twelve 4-inch diameter cores were drilled from each slab. The cylinders were placed in moist curing for an additional week before lab tests

Table B-1
Mix Proportions

Material	Weight per cubic yard of concrete, lb.
Cement	658
Water	320
Fine Aggregate	1070
Coarse Aggregate	1820 (1 1/4" MSA)

Table B-2

Fresh Concrete Properties and Weather Conditions at time of Slab Casting

Slab Number	Slump in.	Air Content %	Unit Weight pcf	Ambient Temperature °F	Relative Humidity %	Wind Velocity Max./Average mph	Penetration Resistance at Revibration, psi	Shrinkage Cracks Present Before Revibration
LL-1	3 1/4	4.80	145	90	32	11/4.8	Control	n.a.
LL-2	3 1/2	4.75	145	90	32	11/4.8	20	yes
LL-3	3 1/4	3.75	145	92	34	19/10.5	60	yes
LL-4	1 3/4	4.30	145	90	30	18/12.4	100	no
LL-5	1 1/2	4.75	146	68	40	22/13.7	150	no
LL-6	4	4.90	146	78	70	17/10.8	300	no
LM-1	3 1/4	4.80	145	90	32	11/4.8	Control	n.a.
LM-2	3 1/4	4.60	145	90	34	19/10.5	60	yes
LM-3	1 3/4	4.80	145	93	30	18/12.4	100	yes
LM-4	2	4.60	145	70	40	22/13.7	150	yes
LM-5	4	4.20	146	82	40	15/10.6	250	no
LM-6	3	4.75	145	80	60	17/10.8	300	no
LH-1	3 1/4	4.80	145	90	32	11/4.8	Control	n.a.
LH-2	2 3/4	4.60	145	90	32	11/4.8	20	no
LH-3	4 1/4	4.80	145	90	34	19/10.5	60	yes
LH-4	2 3/4	4.75	145	90	30	18/12.4	100	yes
LH-5	2 3/4	4.70	145	69	45	22/13.7	150	no
LH-6	2 1/4	4.20	145	82	40	15/10.6	250	no
LH-7	3 1/4	5.00	145	81	60	17/10.8	300	no
M-1	2 1/4	4.70	146	66	28	8/5.5	Control	n.a.
M-2	1 3/4	4.20	146	66	28	8/5.5	60	yes

Table B-2 (Continued)

Slab Number	Slump in.	Air Content %	Unit Weight pcf	Ambient Temperature °F	Relative Humidity %	Wind Velocity Max./Average mph	Penetration Resistance at Revibration, psi	Shrinkage Cracks Present Before Revibration
M-3	3 3/4	4.90	146	66	28	8/5.5	100	yes
M-4	3 3/4	4.30	146	66	28	8/5.5	200	yes
M-5	2 1/4	4.70	146	66	28	8/5.5	350	yes
H-1	2 3/4	4.70	145	71	40	27/12.1	Control	n.o.
H-2	3 3/4	4.70	145	71	40	27/12.1	60	no
H-3	2 1/4	4.80	145	71	40	27/12.1	100	no
H-4	2 1/4	4.75	146	60	50	21/11.9	200	no
H-5	2 1/4	4.60	146	60	50	21/11.9	350	no
H-6	2 1/2	5.00	146	60	50	21/11.9	500	no

Table B-3
Details of the Vibrators

Vibration Designation and Series No.	Frequency hz.	Amplitude in.	Acceleration g	Vibrator & Pan Weight lb.	Force Output lb.
V1	61	.00978	3.6	33	125
V2	110	.00978	12.1	33	400
V3	125	.00978	15.6	33	520
B3	47	.10710	23.8	65	1560
B1	175	.01580	19.4	70	3320

were performed on them. From each slab the following number of specimens and tests were then run:

- 3 specimens for compressive strength tests at 28 days
- 3 specimens for tensile splitting strength at 28 days
- 2 specimens for density measurements
- 1 specimen for air void determination

Standard ASTM tests were used throughout with the modified point count method used in the determination of the air voids.

OBSERVATION OF SURFACE CONDITIONS

The surface of each slab was essentially constant in all cases following casting. However, the surface which was left after revibration was dependent upon penetration resistance and vibrator parameters and, therefore, varied with every slab. The development of shrinkage cracks prior to revibration might be anticipated if one considers the ambient conditions together with the mix design. Such cracks when they did occur before revibration have been noted in Table B-2. Revibration of the surface was 100% effective in closing all visual cracks in the fresh concrete. The speed of the vibrating pan was as near optimal as could be observed visually. That is, that speed at which reliquification of the surface took place and yet sufficiently fast to keep the vibrator afloat, while simultaneously striving to produce the best possible surface condition behind the vibrating pan.

For the vibrator parameters considered and the travel speeds used no apparent segregation took place in any of the slabs; however, at the lower acceleration levels the travel speed was sufficiently slow that a slight accumulation of paste was observed on the top surface. Also at the lower acceleration levels, depth of effectiveness of the revibration was obviously less and therefore depth of reliquification not as extensive. In general, it may be stated that the higher the energy levels vibrators produced the more desirable surface results.

TEST RESULTS

The data obtained from strength and unit weight tests performed on the cores of the revibrated slabs are presented in Table B-4. Graphical presentation of the data is given in Figures B-1 through B-5. Surface revibration of the slabs took place below initial set (400 PSI penetration) with one exception, 500 PSI, and in all instances an increase in compressive and tensile splitting strength was noted at all levels of P.R. for each vibration set of values with one exception where at low P.R. values lower strengths were obtained. The curves drawn for the several series of tests are indicative of apparent trends and are not intended to be statistical curves. There is an evident optimum point at which surface revibration produces a maximum increase in each variable. Where such maximums do occur they tend to be in the general range of 100 to 200 PSI. This would suggest that revibration should be performed as close to 100 psi as practical.

Resolution of the effect of a given acceleration g of a vibrator versus influence on strength and density provides no additional insight in this study.

The air void system of the entrained air is evidently altered somewhat by the surface revibration. However, as one may note from Figure B-6, the only consistency is that the top 0.5 inches apparently have a larger air void spacing than the control. It is also interesting that the most erratic results came on the slabs which were revibrated at higher P.R. values.

Table B-4

Test Data From Cores of Surface Revibrated Slabs

Slab Specimen No.	P.R. at which Revibrated (PSI)	Ave.* 28-Day Compressive Strength (PSI)	Ave.* 28-Day Tensile-Splitting Strength (PSI)	Ave.* Unit Weight (lb./cu. ft.)
LL-1	control	4532	394	140.49
LL-2	20	4589	410	141.72
LL-3	60	4724	434	142.72
LL-4	100	5194	454	143.46
LL-5	150	5408	479	144.89
LL-6	300	5928	471	144.27
LM-1	control	4532	394	140.49
LM-2	60	4772	484	-
LM-3	100	4855	495	142.90
LM-4	150	5017	525	143.21
LM-5	250	5334	530	142.58
LM-6	300	5383	459	141.77
LH-1	control	4532	394	140.49
LH-2	20	4012	377	141.65
LH-3	60	3974	430	142.85
LH-4	100	4642	505	143.35
LH-5	150	4785	500	144.27
LH-6	300	5560	465	143.46
M-1	control	4532	394	140.49
M-2	60	5025	425	141.90
M-3	100	4912	418	141.84
M-4	200	5423	449	142.10
M-5	350	5450	441	141.72
H-1	control	4532	394	140.49
H-2	60	5092	456	141.79
H-3	100	5226	459	141.82
H-4	200	5504	484	143.37
H-5	350	5701	496	143.83
H-6	500	4838	449	142.27

*Average of 2 or more tests.

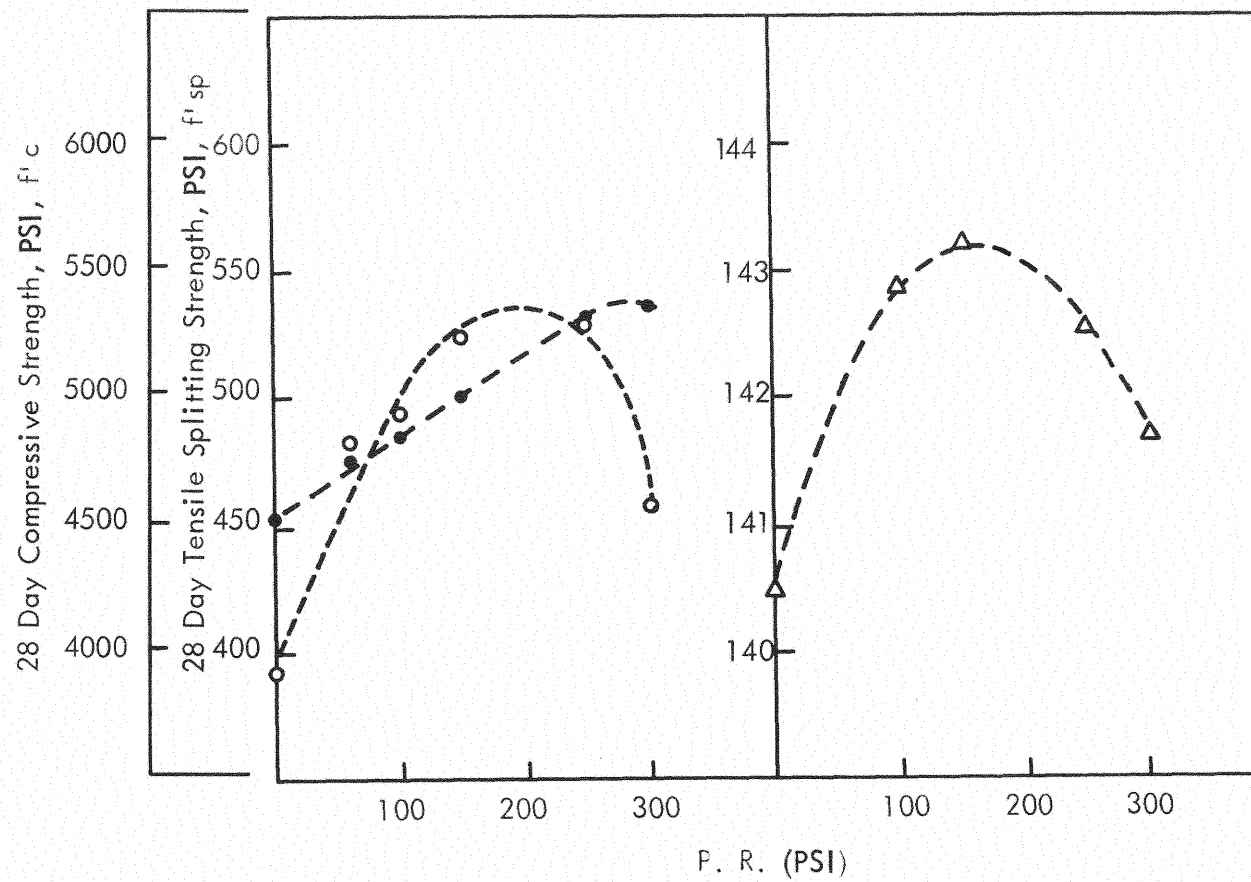


Figure B-2. Graphs of Physical Properties of 4" Diameter Cores Taken from Surface Revibrated Slabs LM at Varying Penetration Resistance.

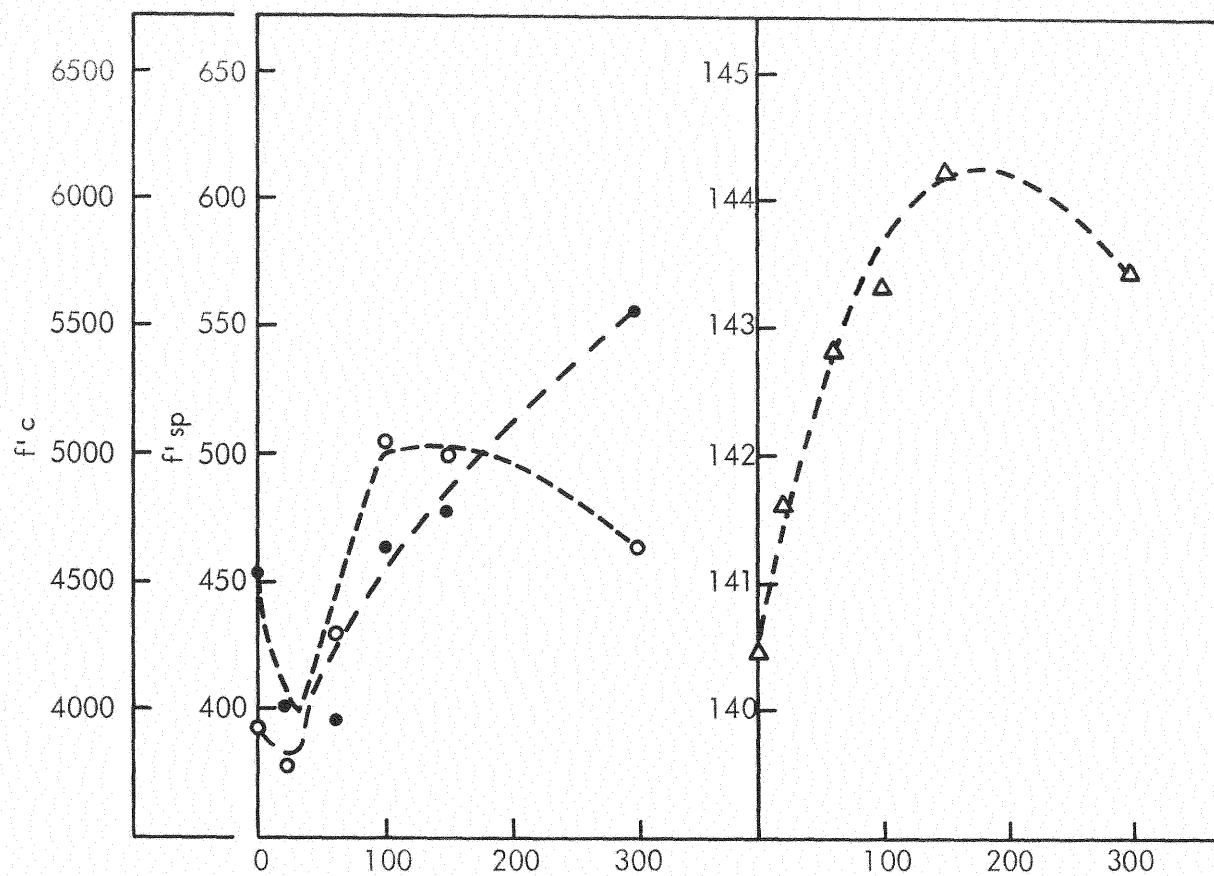


Figure B-3. Graphs of Physical Properties of 4" Diameter Cores Taken from Surface Revibrated Slabs LH at Varying Penetration Resistance.

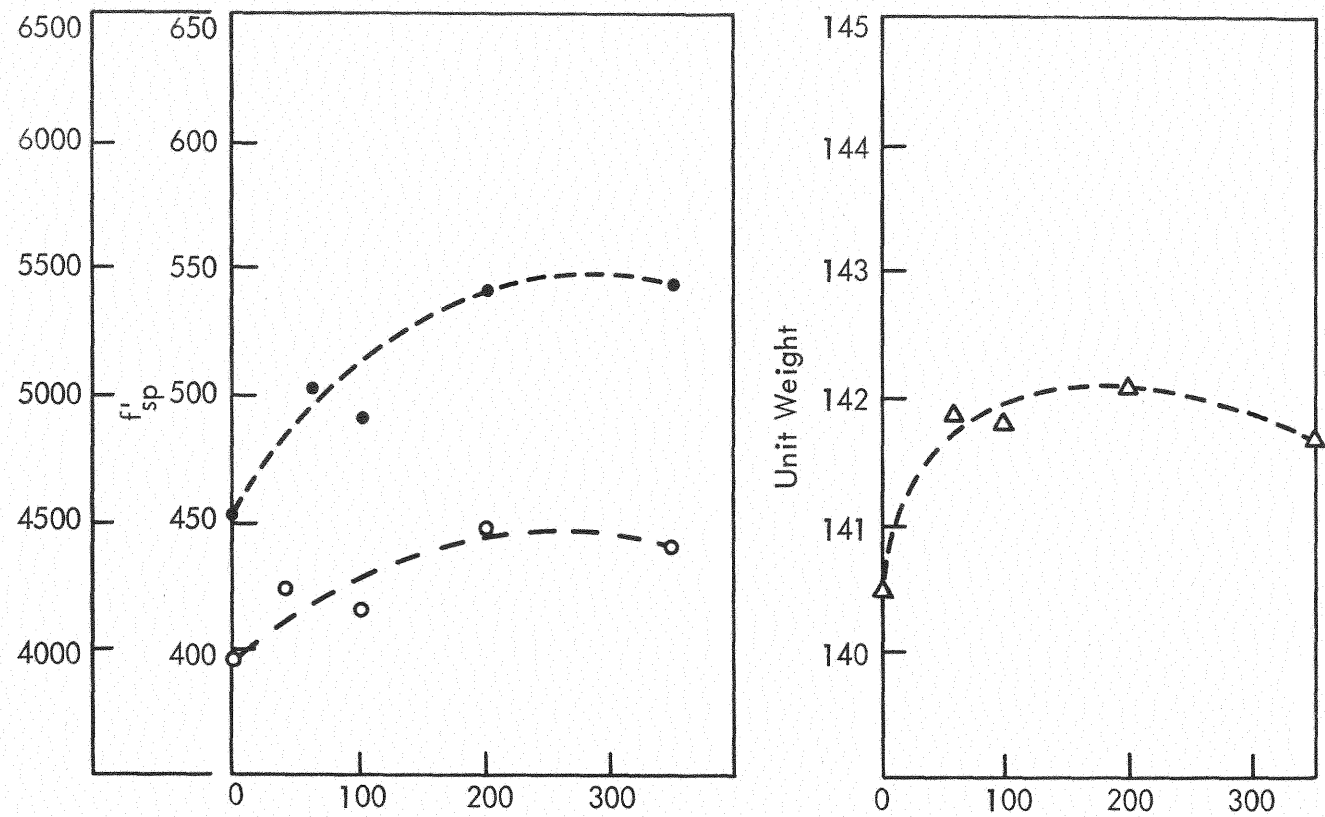


Figure B-4. Graphs of Physical Properties of 4" Diameter Cores Taken from Surface Revibrated Slabs M Varying Penetration Resistance.

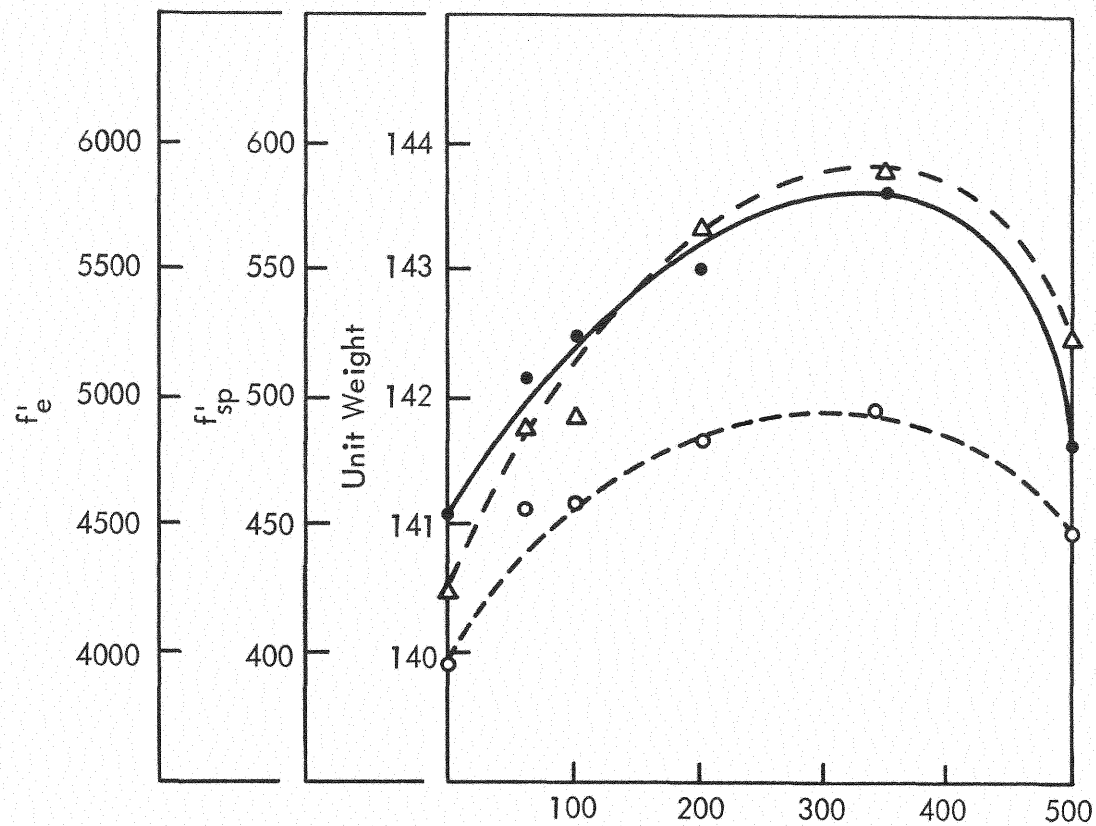


Figure B-5. Graphs of Physical Properties of 4" Diameter Cores Taken from Surface Revibrated Slabs H Varying Penetration Resistance.

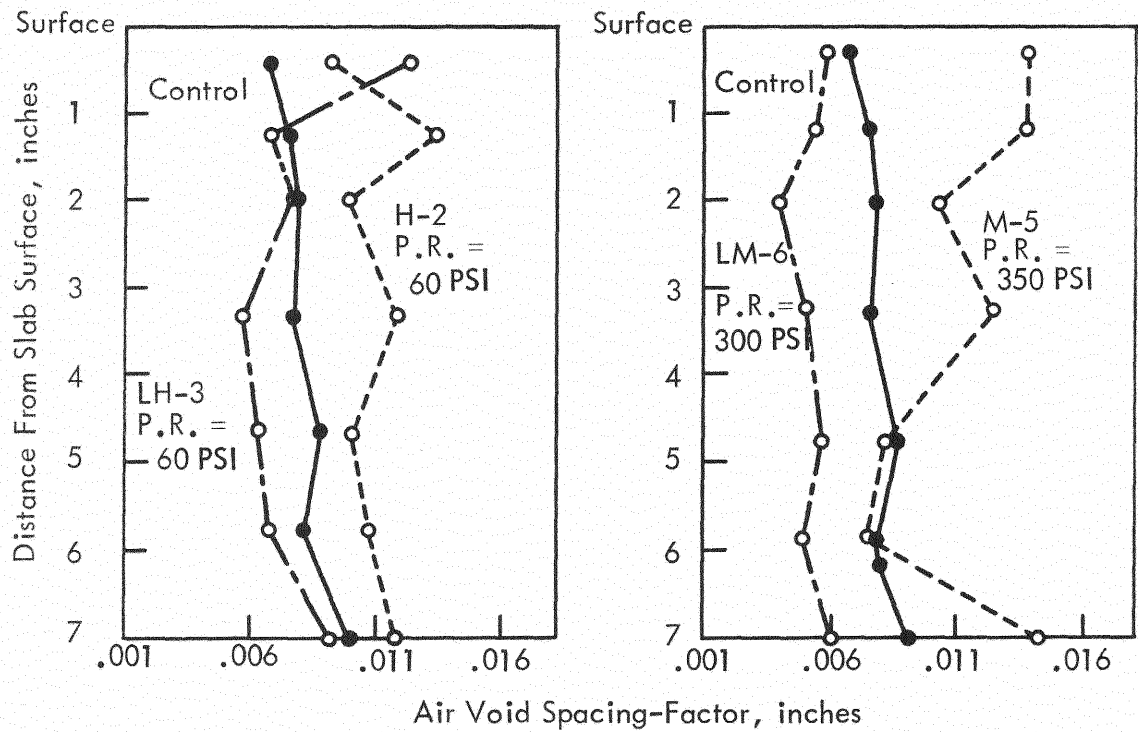


Figure B-6: The Influence of Surface Revibration as Reflected in Air Void Spacing Factor.

CONCLUSIONS

Surface revibration of concrete slabs improves the compressive strength and tensile strength of cylinders of cores taken from such slabs as much as 30% over control slabs.

Optimal revibration for increased strength should be performed between 100 PSI and 200 PSI penetration resistance. However, each vibration energy has a unique optimum. Surface revibration of slabs improved the density of the concrete in this study up to a maximum of 3% with the optimum occurring at approximately 100 to 200 PSI penetration resistance. Surface revibration has detrimental effects if performed when P.R. has gone beyond about 300 PSI.

For the travel speeds investigated, vibrators with an energy output between 10 and 20 g appear to perform best and produce the best resulting surface for eventual finishing. Surface revibration can be performed so as to produce little if any segregation of mixed constituents. Difficulty is encountered in the finishing of slabs revibrated beyond 100 PSI penetration resistance due to the stiffness of the mass.

COMPUTATION OF VIBRATOR OUTPUT

To determine force output from a vibrator, start with the basic approach:

$$F = ma \quad \text{where, } m = \text{mass, (lb-sec}^2/\text{in)} \\ a = \text{acceleration, (in/sec}^2)$$

by definition,

$$m = \frac{W}{g} \quad \text{where, } W = \text{weight of eccentric, (lb)} \\ g = \text{gravitational acceleration, (386 in/sec}^2\text{).}$$

by definition,

$$a = r\omega^2 \quad \text{where, } r = \text{radius from rotating center to center of rotating mass, (in)} \\ \omega = \text{angular velocity in radian/sec} \\ \left(2\pi \times \frac{\text{rpm}}{60}\right)$$

therefore,

$$F = ma \\ = \frac{W}{g} \times r \times \left(2\pi \times \frac{\text{rpm}}{60}\right)^2 \\ = W \times r \times 4\pi^2 \left(\frac{\text{rpm}}{3600 \times 386}\right)^2 \\ = W \times r \times 2.8557 \times 10^{-5} \times \text{rpm}^2$$

Now, computed average amplitude, $A = \frac{Wr}{W + \omega}$, in

where, $W + \omega = \text{total weight of vibrator and pan, lb.}$

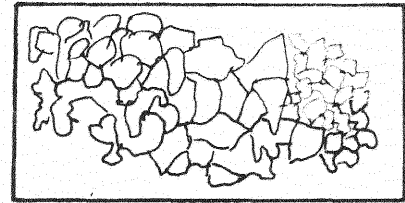
BACKGROUND REFERENCES

The following references are of value in putting Appendix B in perspective with previous work. In addition to these articles, the reader is also referred to those listed in Appendix A.

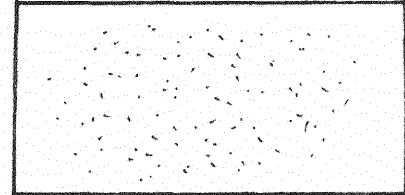
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LEGEND

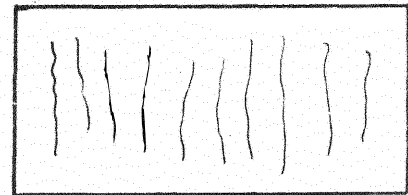
LIGHT TO MODERATE CRAZING



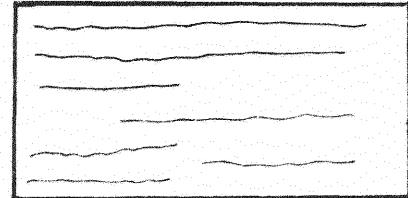
LIGHT TO MODERATE FLAKING



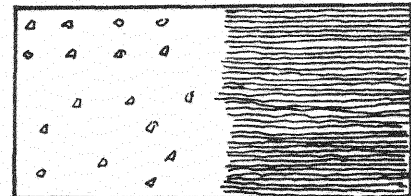
TRANSVERSE CRACKING



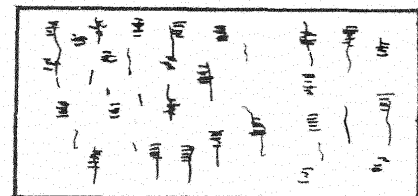
LONGITUDINAL CRACKING



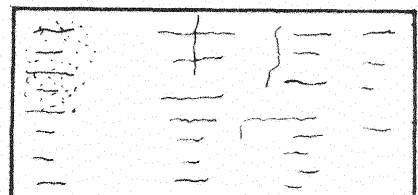
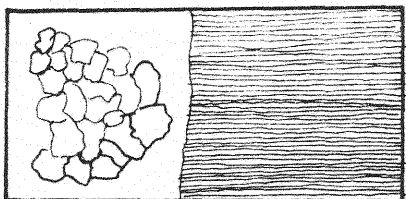
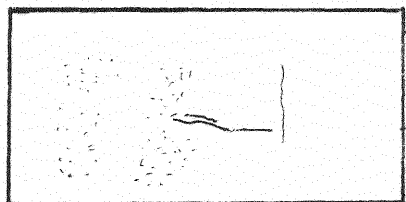
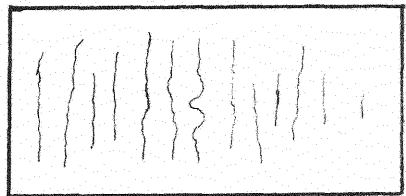
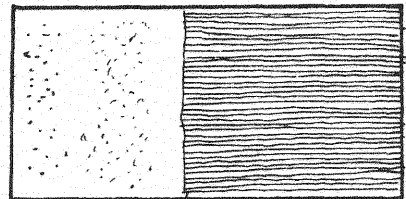
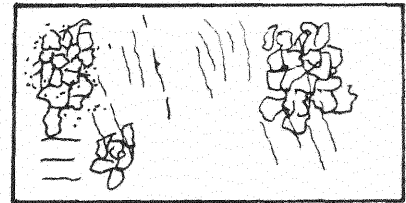
SURFACE VOIDS (CAUSED BY DISPLACED AGGREGATE DURING SURFACE REVIBRATION OF STIFF CONCRETES) AND BROOMED SURFACE



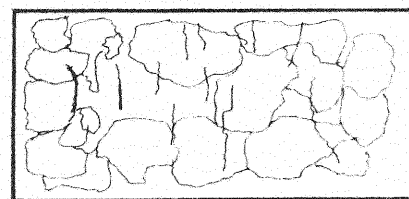
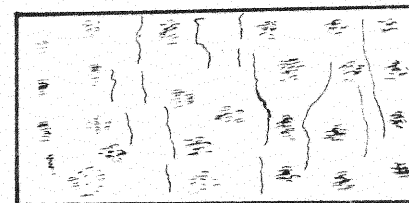
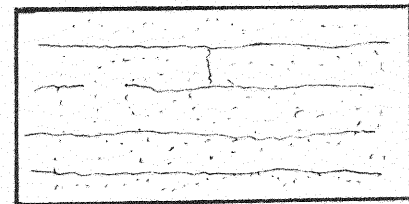
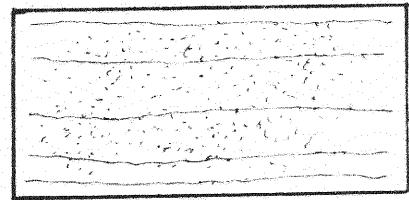
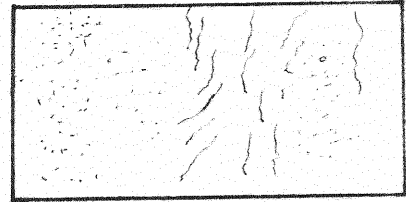
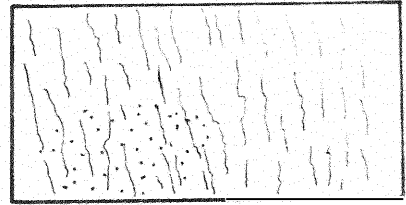
RANDOM, TRANSVERSE CRACKS AND MODERATE SCALING



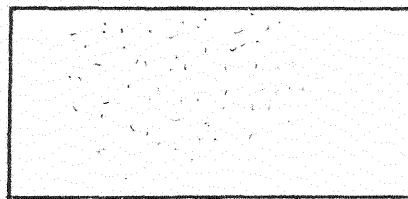
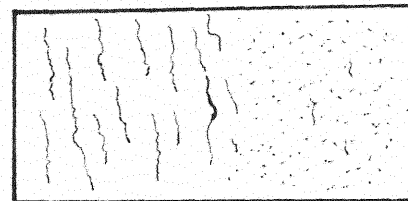
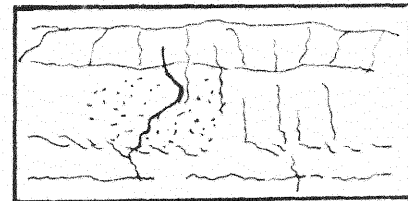
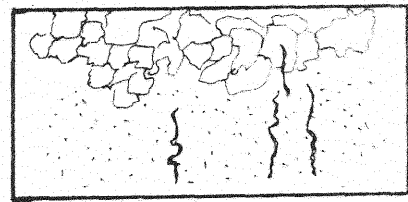
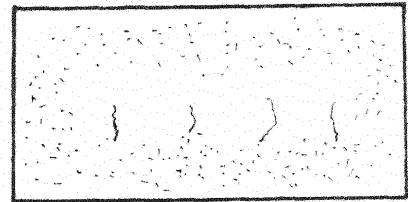
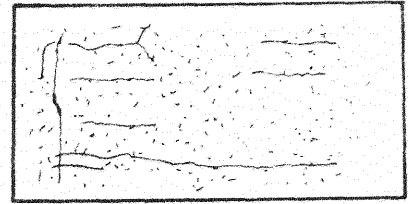
Slab Type and Number	Water/Cement Ratio	Top Reinforcing Cover (inches)	Penetration Resistance at Revibration Time (PSI)
DS-1	0.6	1.0	
DS-2	0.6	0.75	
DS-3	0.6	0.75	
DS-4	0.6	0.75	
DS-5	0.6	0.75	
DS-6	0.68	0.75	



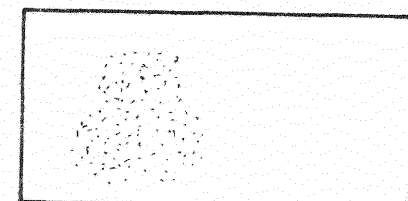
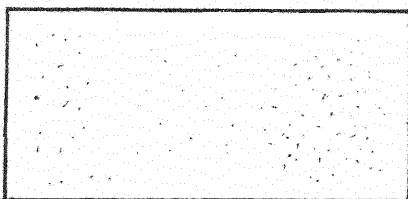
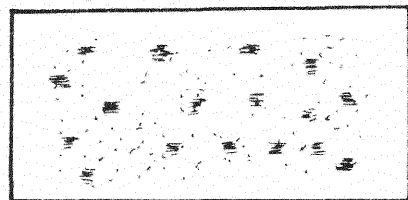
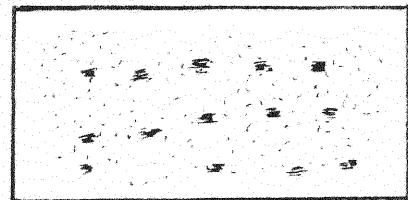
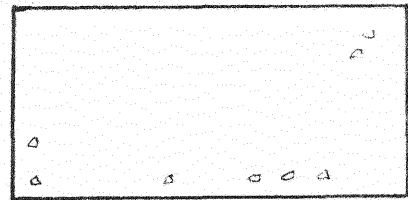
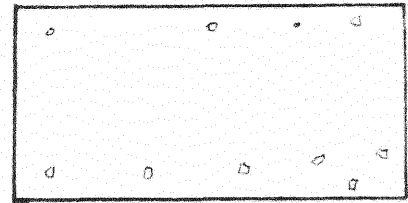
Slab Type and Number	Water/Cement Ratio	Top Reinforcing Cover (inches)	Penetration Resistance at Revibration Time (PSI)
DS-7	0.68	0.75	
DS-8	0.68	0.5	
DS-9	0.68	0.5	
DS-10	0.68	0.75	
DS-11	0.68	None	
DS-12	0.45	0.5	



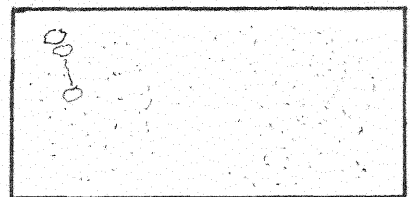
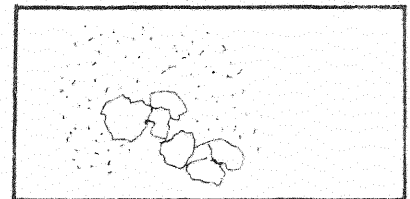
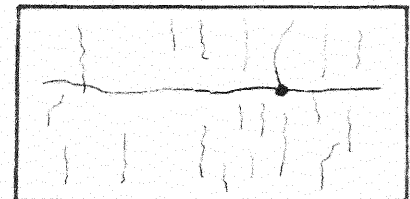
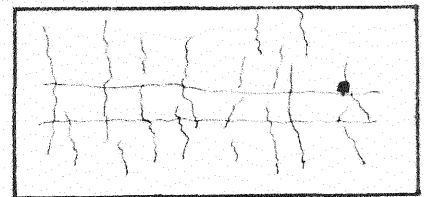
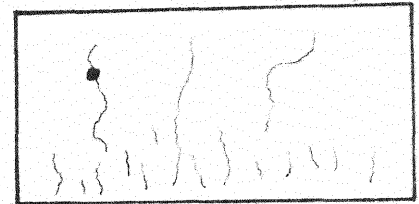
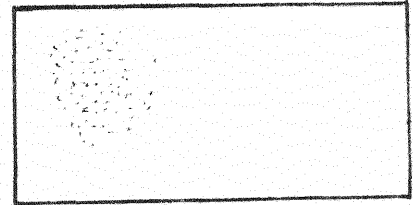
Slab Type and Number	Water/ Cement Ratio	Top Reinforcing Cover (inches)	Penetration Resistance at Revibration Time (PSI)
DS-13	0.45	0.5	
DS-14	0.45	None	
DS-15	0.68	0.5	
DS-16	0.68	0.5	
DS-17	0.68	0.5	
DS-20	0.48	1.25	



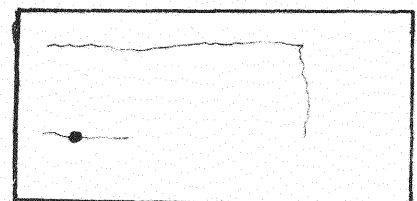
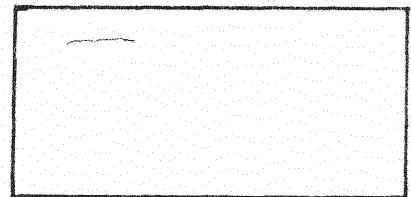
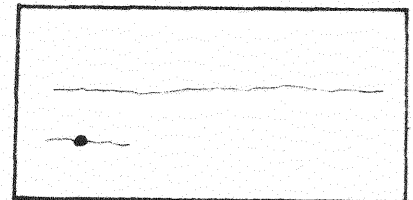
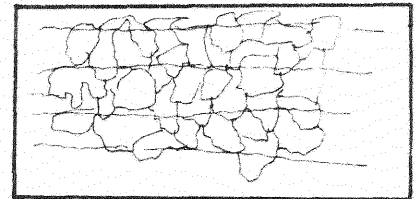
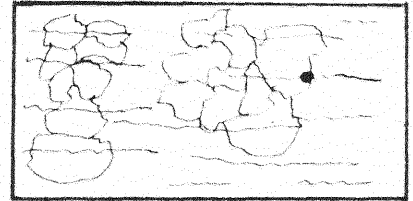
Slab Type and Number	Water/ Cement Ratio	Top Reinforcing Cover (inches)	Penetration Resistance at Revibration Time (PSI)
DS-22	0.48	1.5	
DS-23	0.48	1.0	
DS-24	0.84	1.5	
DS-25	0.84	0.5	
DS-26 DS-27	0.84	0.5 1.5	
DS-29	0.42	1.0	



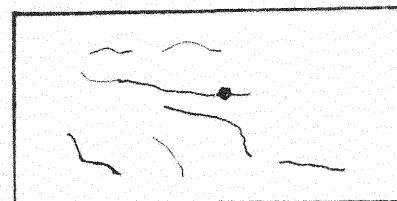
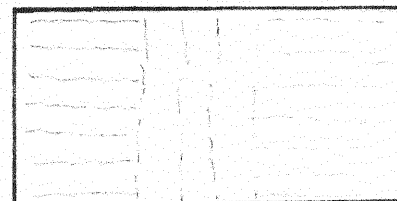
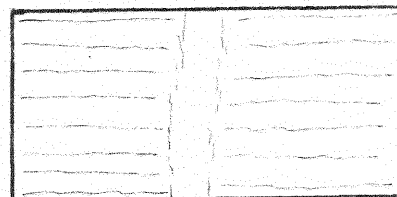
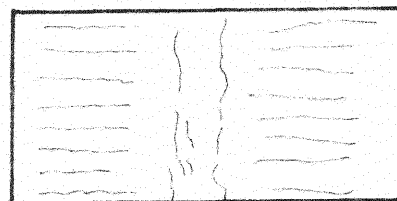
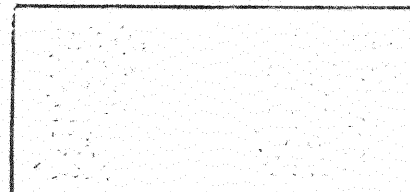
Slab Type and Number	Water/Cement Ratio	Top Reinforcing Cover (inches)	Penetration Resistance at Revibration Time (PSI)
DS-32	0.62	1.75	
DS-33	0.73	1.75	
DS-34	0.73	0.5	
DS-35	0.73	0.5	
DS-36	0.59	1.5	
DS-37	0.59	1.5	



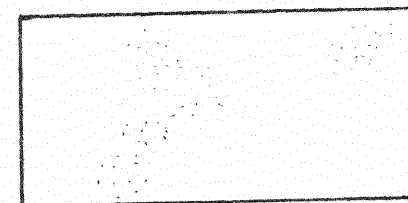
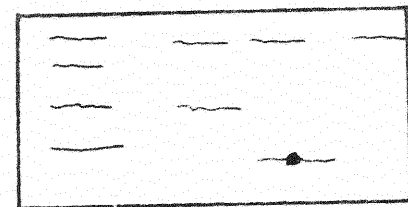
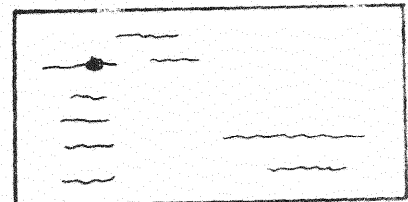
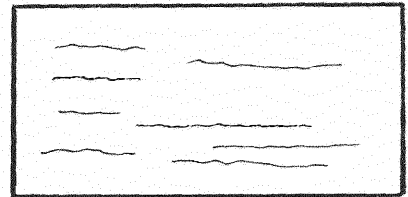
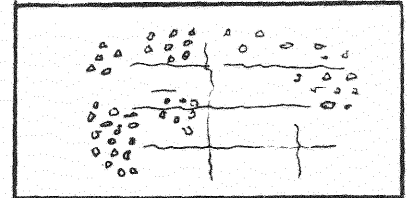
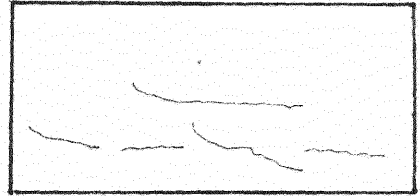
Slab Type and Number	Water/ Cement Ratio	Top Reinforcing Cover (inches)	Penetration Resistance at Revibration Time (PSI)
DS-38	0.59	0.5	
DS-37	0.59	0.5	
DS-40	0.4	1.5	
DS-42	0.4	0.5	
DS-43	0.4	0.5	
DS-46	0.61	1.5	



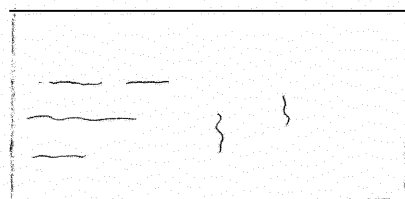
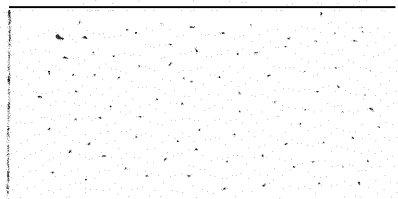
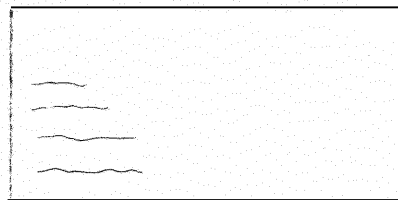
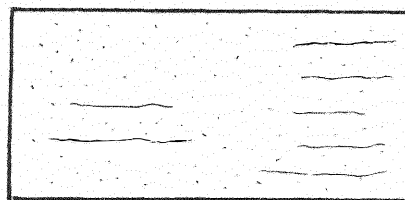
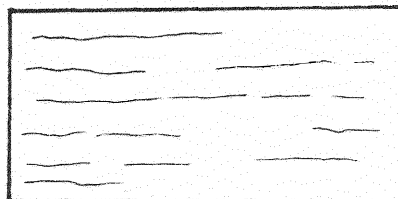
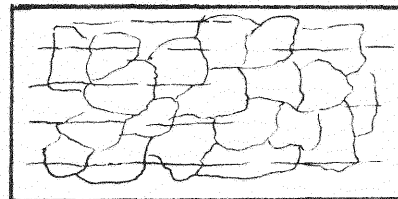
Slab Type and Number	Water/Cement Ratio	Top Reinforcing Cover (inches)	Penetration Resistance at Revibration Time (PSI)
DS-47	0.61	0.5	
DS-48	0.47	1.5	
DS-49	0.47	1.5	
DS-50	0.47	0.5	
DS-51	0.47	0.5	
DS-52	0.77	1.5	



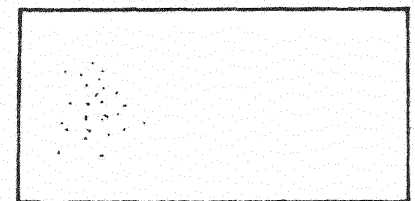
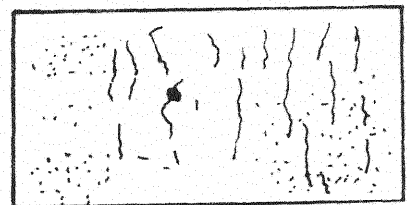
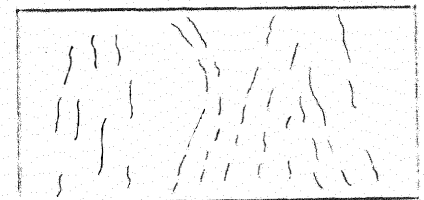
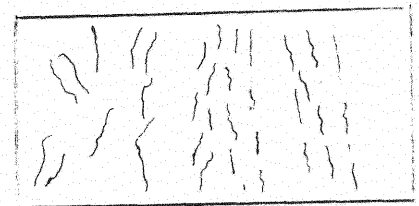
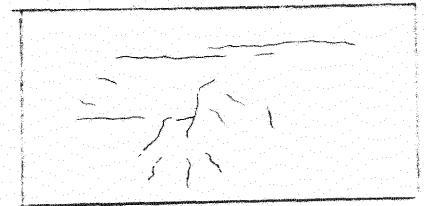
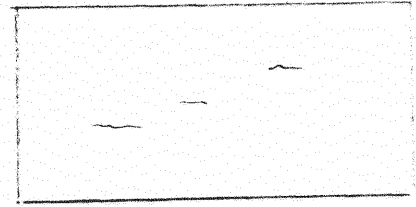
Slab Type and Number	Water/ Cement Ratio	Top Reinforcing Cover (inches)	Penetration Resistance at Revibration Time (PSI)
DS-53	0.77	1.5	
DS-54	0.77	0.5	
DS-55	0.77	0.5	
DS-72	0.55	0.5	
DS-75	0.55	1.5	
DS-77	0.54	1.5	



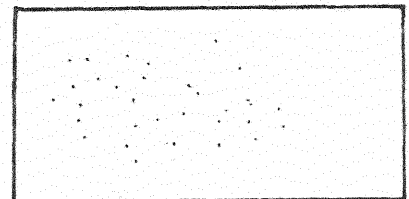
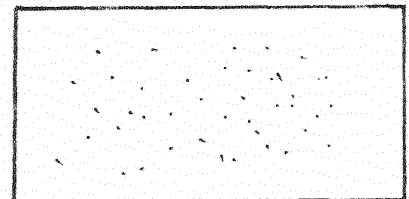
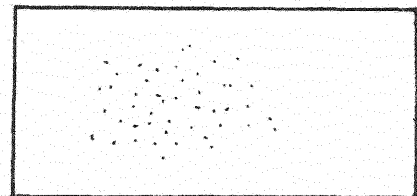
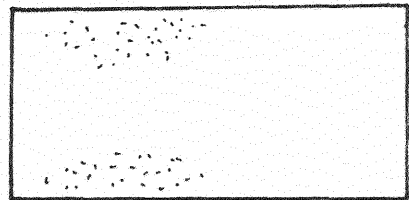
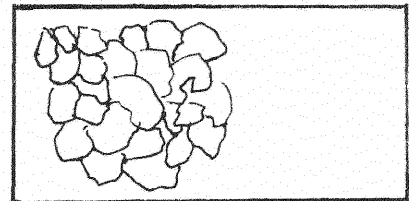
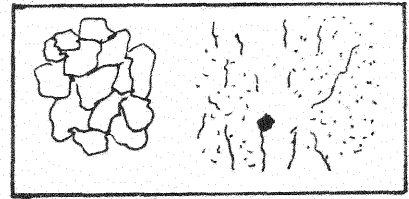
Slab Type and Number	Water/ Cement Ratio	Top Reinforcing Cover (inches)	Penetration Resistance at Revibration Time (PSI)
DS-81	0.6	0.5	
DSR-1	0.43	0.5	
DSR-2	0.41	0.5	
DSR-7	0.7	0.5	
DSR-13	0.75	1.5	
DSR-14	0.66	1.5	



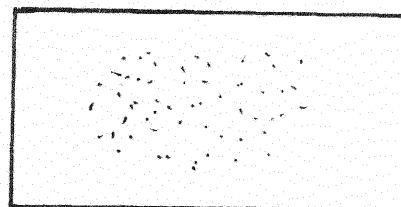
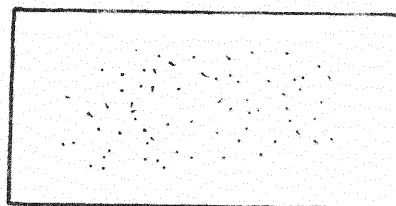
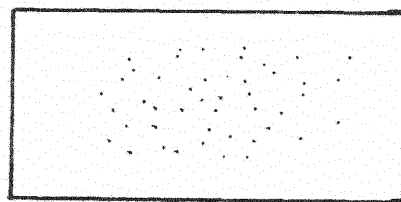
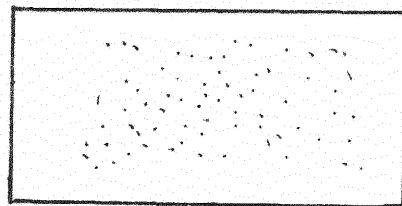
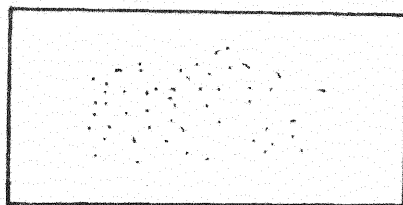
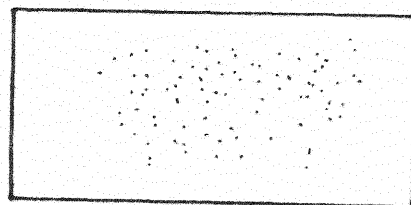
Slab Type and Number	Water/ Cement Ratio	Top Reinforcing Cover (inches)	Penetration Resistance at Revibration Time (PSI)
DSR-15	0.47	1.5	
RVS-1	0.77	0.5	25
RVS-2	0.77	0.5	50
RVS-3	0.77	1.5	99
RVS-4	0.77	0.5	200
RVS-6	0.67	1.0	50



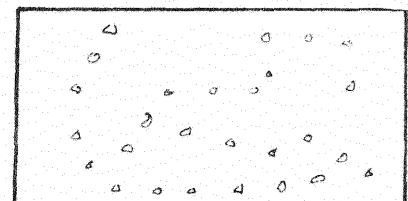
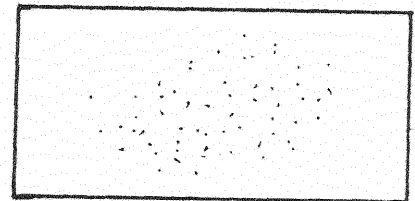
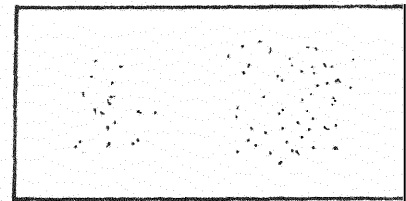
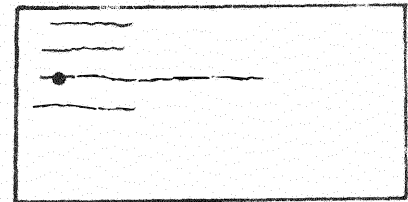
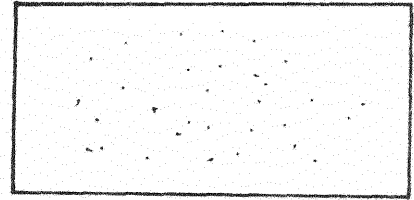
Slab Type and Number	Water/ Cement Ratio	Top Reinforcing Cover (inches)	Penetration Resistance at Revibration Time (PSI)
RVS-8	0.67	0.5	200
RVS-12	0.66	0.5	200
RVS-13	0.55	0.5	30
RVS-21	0.61	0.5	30
RVS-22	0.61	1.5	60
RVS-25	0.61	0.5	35



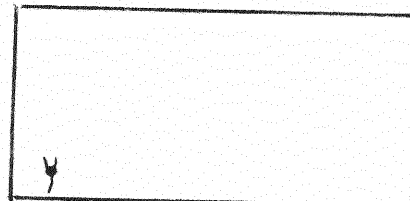
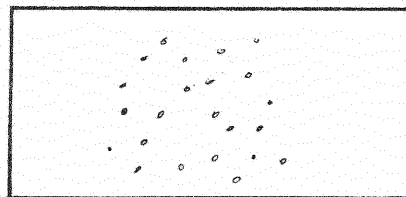
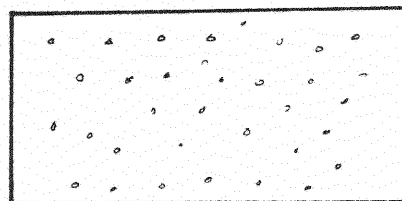
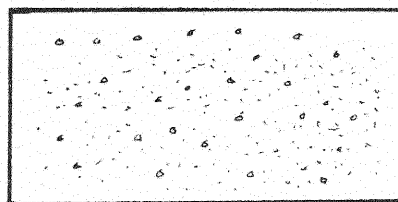
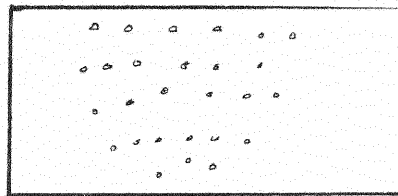
Slab Type and Number	Water/ Cement Ratio	Top Reinforcing Cover (inches)	Penetration Resistance at Revibration Time (PSI)
RVS-26	0.61	1.5	90
RVS-27	0.61	0.5	108
RVS-30	0.59	1.5	70
DS-59	0.59	0.5	None
DS-60	0.59	1.5	None
DS-61	0.59	0.5	None



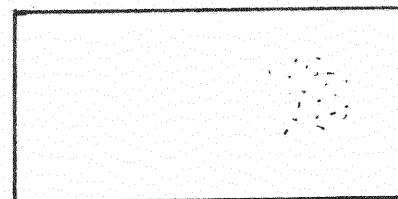
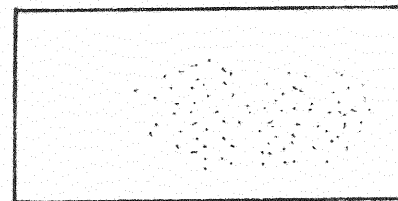
Slab Type and Number	Water/ Cement Ratio	Top Reinforcing Cover (inches)	Penetration Resistance at Revibration Time
DS-62	0.70	1.5	None
DS-64	0.55	1.5	None
RVS-33	0.59	0.5	32
RVS-34	0.59	1.5	70
RVS-39	0.70	1.5	90



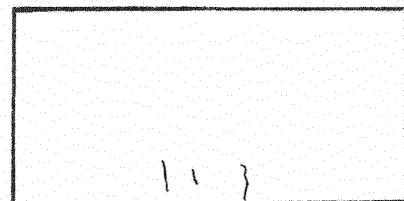
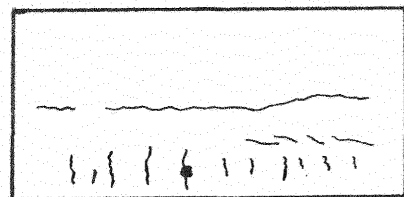
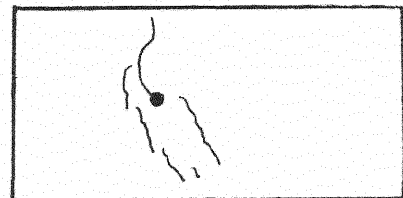
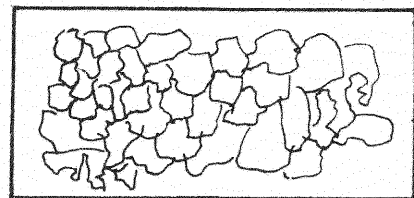
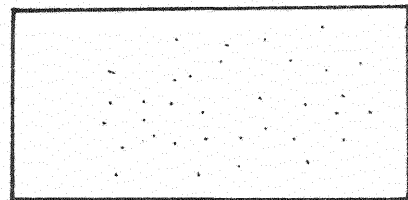
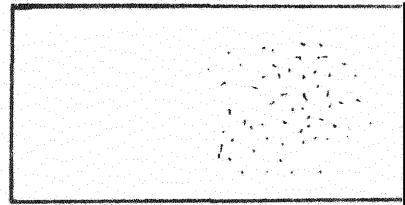
Slab Type and Number	Water/ Cement Ratio	Top Reinforcing Cover (inches)	Penetration Resistance at Revibration Time (PSI)
RVS-53	0.55	0.5	30
RVS-54	0.55	1.5	65
RVS-55	0.55	0.5	100
RVS-56	0.55	1.5	120
RVS-58	0.55	1.5	60



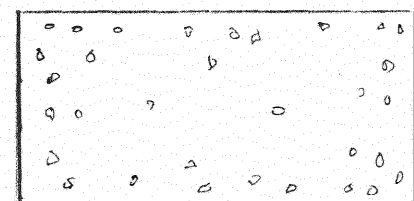
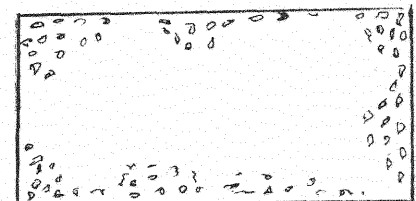
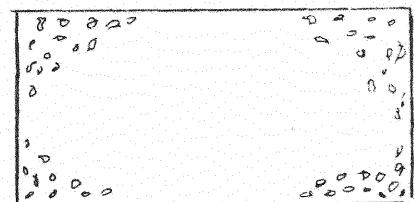
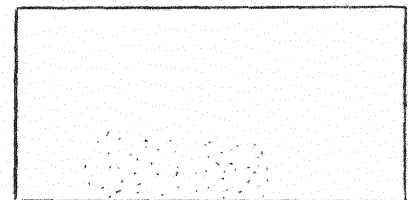
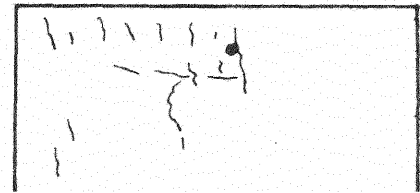
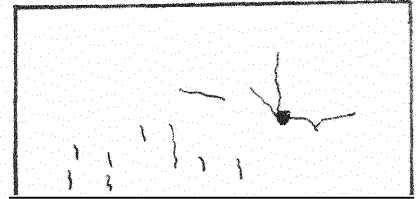
Slab Type and Number	Water/ Cement Ratio	Top Reinforcing Cover (inches)	Penetration Resistance at Revibration Time (PSI)
RVS-61	0.49	0.5	28
RVS-62	0.49	0.5	65



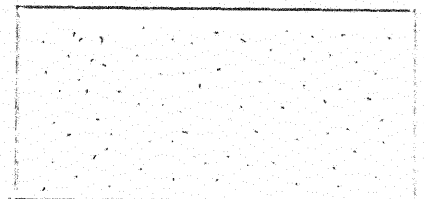
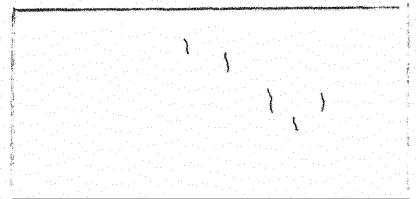
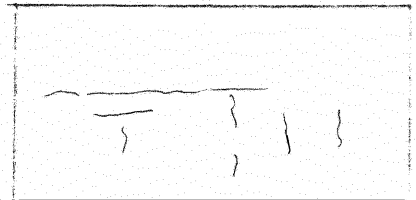
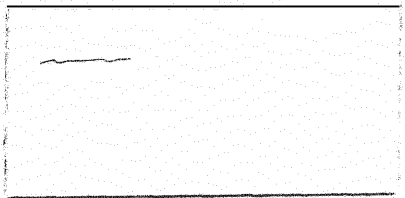
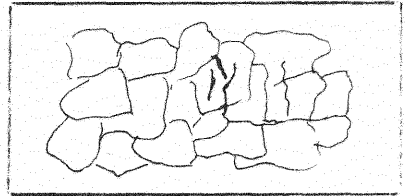
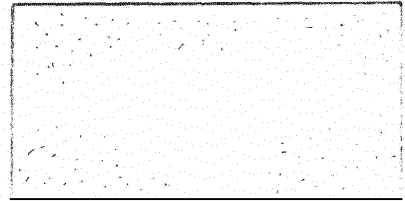
Slab Type and Number	Water/ Cement Ratio	Top Reinforcing Cover (inches)	Penetration Resistance at Revibration Time (PSI)
RVS-63	0.49	-	95
RVS-64	0.49	1.5	120
RVS-67	0.49	1.5	55
RVS-77	0.43	1.5	30
RVS-85	0.43	1.5	35
RVS-89	0.7	0.5	30
RVS-90	0.7	1.5	42



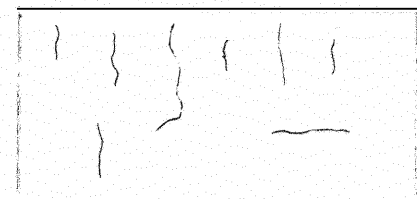
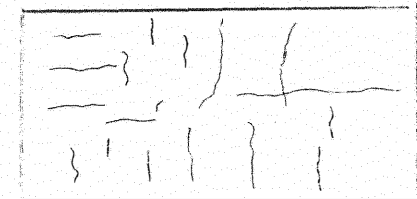
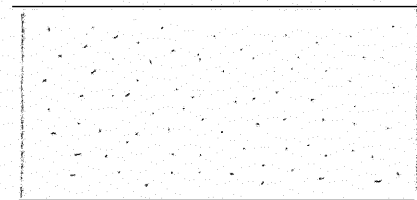
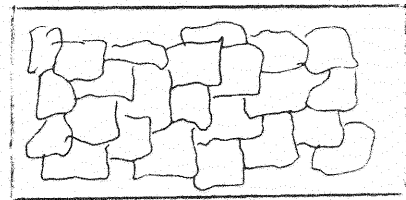
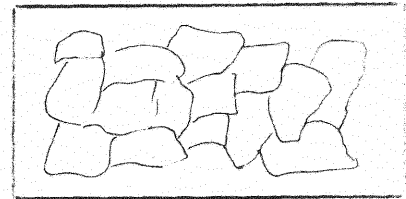
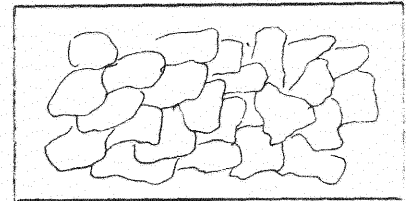
Slab Type and Number	Water/ Cement Ratio	Top Reinforcing Cover (inches)	Penetration Resistance at Revibration Time (PSI)
RVS-94	0.8	1.5	60
RVS-95	0.8	0.5	70
RVS-99	0.7	1.5	60
RVSR-1	0.43	1.5	30
RVSR-2	0.43	0.5	60
RVSR-3	0.43	1.5	100



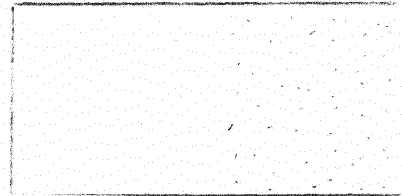
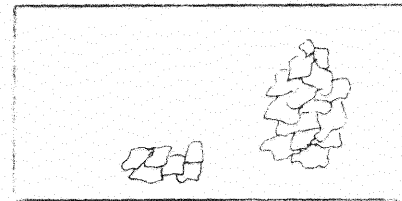
Slab Type and Number	Water/ Cement Ratio	Top Reinforcing Cover (inches)	Penetration Resistance at Revibration Time (PSI)
RVSR-6	0.43	0.5	22
RVSR-8	0.43	1.5	100
RVSR-12	0.53	0.5	10
RVSR-14	0.53	0.5	18
RVSR-15	0.53	1.5	18
RVSR-16	0.65	1.5	70



Slab Type and Number	Water/ Cement Ratio	Top Reinforcing Cover (inches)	Penetration Resistance at Revibration Time (PSI)
RVSR-17	0.65	0.5	100
RVSR-20	0.7	0.5	40
RVSR-21	0.7	1.5	80
RVSR-25	0.75	1.5	10
RVSR-26	0.75	0.5	20
RVSR-27	0.75	1.5	15



Slab Type and Number	Water/ Cement Ratio	Top Reinforcing Cover (inches)	Penetration Resistance at Revibration Time (PSI)
RVSR-30	0.66	1.5	10
RVSR-33	0.47	1.5	45



APPENDIX D

SLAB DATA SHEET

APPENDIX D

SLAB DATA SHEET

OURI PROJECT NO. 1774

SLAB NO: _____ [Shown on top side, lower left slab corner]

CAST DATE AND TIME: _____ day _____ month _____ year; _____ A.M./P.M.

CAST DATE WEATHER: Temperature,

Dry bulb _____ °F
Relative Humidity _____ %

1. Concrete Data:

(a) Proportions:

As delivered

Per Cubic Yard

Cement _____ #	_____ # w/c =
Water _____ #	_____ # p/a =
Sand (SSD) _____ #	_____ #
Gravel (SSD) _____ #	_____ 1 cubic yard

(b) Admixtures:

Air Entrainment, brand _____
Amount _____ % (by weight of cement)
Retarder, brand _____
Amount _____ %
Other: _____

(c) Properties:

Slump _____ " (ave. _____ trials)
Unit Weight _____ (ave. _____ trials)

(Temperature of Fresh Concrete Delivered: _____ °F.)

Cylinder Compressive Strength Data:

Test Cylinder Size _____

Age _____ Days	Age _____ Days	Age _____ Days
1 _____ psi	1 _____ psi	1 _____ psi
2 _____ psi	2 _____ psi	2 _____ psi
3 _____ psi	3 _____ psi	3 _____ psi
Ave. _____ psi	Ave. _____ psi	Ave. _____ psi

(d) Other Data: _____

2. Reinforcement Data:

- (a) Top Mat; bar size No. _____; Spacing, long. _____" latr. _____"
Upper bar runs longitudinally or laterally?
Average Clear Cover _____"
- (b) Bottom mat; bar size No. _____; Spacing, long. _____" latr. _____"
Lower bar runs longitudinally or laterally?
Average clear cover _____"
- (c) Other Data _____

3. Slab Data:

- (a) Total Length _____
No. of Spans _____ Span Lengths _____
- (b) Form work material _____
A' Priori Casting, form surface preparation _____
- (c) Dead load deflection at centre span, 1 _____
(Note: span 1 same end as slab legend corner) 2 _____
3 _____
- (d) Induced deflection (jacking) _____ inches

4. Placement data:

- Time placement started _____ A.M.
_____ P.M.
- (a) Internal vibration during placement: Yes _____ No _____
How much? _____
Type of vibrator used _____ Size _____
- (b) Type of Screeding: Hand Screeding _____
Vibrator Screeding _____
No. of Passes _____

Vibrator Screeding Frequency _____
 Amplitude _____
 Travel Speed _____

Surface Appearance after screeding _____
Screeded how many times _____

(c) Internal vibration after screeding yes _____ no _____
How much _____

(d) Surface Vibration (other than initial screeding):
(Sketch and describe the vibrator arrangement noting all pertinent data)

Frequency: _____ cps ^{or}/cpm
Amplitude: _____ inches
Travel Speed: _____ ft/min.
No. Passes: _____
Describe resulting surface: _____

(e) Finishing Details:
Floated: Yes _____ No _____
No. of Passes: _____
Troweled: Yes _____ No _____
How Much: _____
Broomed: Yes _____ No _____
Other Finish: _____

(f) Other Data:

5. Revibration Data:

(a) Time lapse from cast to start of revibration _____;
to end _____.

(b) Penetration resistance at start of revibration _____ psi

- (c) Sketch vibrator arrangement with pertinent dimensions.
- (d) Vibration frequency _____ Amplitude _____
(at the screed-concrete interface)
- (e) Vibrator travel-speed _____
- (f) Repasses, number _____
Changes in (c) and (d) _____

6. Surface Appearance (crack history)

(attach photographs and see items 8.)

- (a) Comments and sketches (see item 8) of slab surface from initial cast though final set noting appearance, cracking, time, etc. (Development of cracks, surface appearance before revibration and after, such as sandy surface, rough textured surface due to exposure of aggregates, smooth surface due to accumulation of excess paste, varying or undulating surfaces caused by the movement of the vibrator, blistering of the surface due to excess water, etc., may be noted.)

- (b) Post-final set visible cracking.

- 1. Time and date of observation _____
- 2. Sketch crack pattern in a separate sheet (if not apparent on photo)
- 3. Apparent type of crack:
(List possibilities)
- 4. Crack size: Max length _____ "
Approximate average length _____ "
Max. Crack width _____ " (shown where located)
Approximate average width _____ "
- 5. No. of cracks, total: _____
- 6. Other comments:

- (c) Changes in cracking observed on subsequent dates:

- 1. Time and date of observation _____

2. Sketch and/or photo
 3. Comment on items 3,4, and 5 of part (b) preceding this:
 4. Other comments --including interim weather; (use separate sheet)
-
7. Core taken or cut surfaces observed:
 - (a) Date
 - (b) Location in slab
 - (c) Other comments:
-
8. Sketch of slab cracking, and other items of interest (see separate pages)